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PROCEEDINGS

of

The Institute of Radio Engineers

1929 CONVENTION
Washington, D.C.
May 13-15th

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Institute of Radio Engineers

Forthcoming Meetings

ATLANTA SECTION
Atlanta, Georgia, January 9, 1929

BUFFALO-NIAGARA SECTION
Buffalo, N. Y., January 17, 1929

TORONTO SECTION
Toronto, Ontario, January 16, 1929

CHICAGO SECTION
Chicago, Ill., January 11, 1929

CLEVELAND SECTION
Cleveland, Ohio, January 18, 1929

DETROIT SECTION
Detroit, Mich., January 18, 1929

LOS ANGELES SECTION
Los Angeles, Calif., January 17, 1929

NEW YORK MEETING
New York, N. Y., January 2, 1929 and February 6, 1929

PHILADELPHIA SECTION
Philadelphia, Penna., January 25, 1929

PITTSBURGH SECTION
Pittsburgh, Penna., January 21, 1929

ROCHESTER SECTION
Rochester, N. Y., January 11, 1929

WASHINGTON SECTION
Washington, D. C., January 10, 1929

PROCEEDINGS OF
The Institute of Radio Engineers

Volume 17 January, 1929 Number 1

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The Institute of Radio Engineers

GENERAL INFORMATION

The PROCEEDINGS of the Institute is published monthly and contains papers and discussions thereon submitted for publication or for presentation before meetings of the Institute or its Sections. Payment of the annual dues by a member entitles him to one copy of each number of the PROCEEDINGS issued during the period of his membership.

Subscription rates to the PROCEEDINGS for the current year are received from nonmembers at the rate of $1.00 per copy or $10.00 per year. To foreign countries the rates are $1.10 per copy or $11.00 per year.

Back issues are available in unbound form for the years 1918, 1920, 1921, 1922, 1923, and 1926 at $9.00 per volume (six issues) or $1.50 per single issue. Single copies for the year 1928 are available at $1.00 per issue. For the years 1913, 1914, 1915, 1916, 1917, 1918, 1924, and 1925 miscellaneous copies (incomplete unbound volumes) can be purchased for $1.50 each; for 1927 at $1.00 each. The Secretary of the Institute should be addressed for a list of these.

Discount of twenty-five per cent on all unbound volumes or copies is allowed to members of the Institute, libraries, booksellers, and subscription agencies.

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Year Books for 1926, 1927, and 1928, containing general information, the Constitution and By-Laws, catalog of membership, etc., are priced at seventy-five cents per copy per year.

Contributors to the PROCEEDINGS are referred to the following page for suggestions as to approved methods of preparing manuscripts for publication in the PROCEEDINGS.

Advertising rates to the PROCEEDINGS will be supplied by the Institute's Advertising Department, Room 802, 33 West 39th Street, New York, N. Y.

Changes of address to affect a particular issue must be received at the Institute office not later than the 15th of the month preceding date of issue. That is, a change in mailing address to be effective with the October issue of the PROCEEDINGS must be received by not later than September 15th. Members of the Institute are requested to advise the Secretary of any change in their business connection or title irrespective of change in their mailing address, for the purpose of keeping the Year Book membership catalog up to date.

The right to reprint limited portions or abstracts of the papers, discussions, or editorial notes in the PROCEEDINGS is granted on the express condition that specific reference shall be made to the source of such material. Diagrams and photographs published in the PROCEEDINGS may not be reproduced without making special arrangements with the Institute through the Secretary.

It is understood that the statements and opinions given in the PROCEEDINGS are views of the individual members to whom they are credited, and are not binding on the membership of the Institute as a whole.

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SUGGESTIONS FOR CONTRIBUTORS TO THE PROCEEDINGS

Preparation of Paper

Form—Manuscripts may be submitted by member and non-member contributors from any country. To be acceptable for publication manuscripts should be in English, in final form for publication, and accompanied by a summary of from 100 to 300 words. Papers should be typed double space with consecutive numbering of pages. Footnote references should be consecutively numbered, and should appear at the foot of their respective pages. Each reference should contain author's name, title of article, name of journal, volume page, month, and year. Generally, the sequence of presentation should be as follows: statement of problem; review of the subject in which the scope, object, and conclusions of previous investigations in the same field are covered; main body describing the apparatus, experiments, theoretical work, and results used in reaching the conclusions conclusions and their relation to present theory and practice; bibliography. The above pertains to the usual type of paper. To whatever type a contribution may belong a close conformity to the spirit of these suggestions is recommended.

Illustrations—Use only jet black ink on white paper or tracing cloth. Cross-section paper used for graphs should not have more than four lines per inch. If finer ruled paper is used, the major division lines should be drawn in with black ink, omitting the finer devisions. In the latter case, only blue-lined paper can be accepted. Photographs must be very distinct, and must be printed on glossy white paper. Blueprinted illustrations of any kind cannot be used. All lettering should be $^3/_{16}$ in. high for an 8 x 10 in. figure. Legends for figures should be tabulated on a separate sheet, not lettered on the illustrations.

Mathematics—Fractions should be indicated by a slanting line. Use standard symbols. Decimals not preceded by whole numbers should be preceded by zero, as 0.016. Equations may be written in ink with subscript numbers, radicals, etc., in the desired proportions.

Abbreviations—Write a.c. and d.c., kc, μf, $\mu\mu$f, emf, mh, μh, henries, abscissas, antennas Refer to figures as Fig. 1, Figs. 3 and 4, and to equations as (5). Number equations on the right, in parentheses.

Summary—The summary should contain a statement of major conclusions reached, since summaries in many cases constitute the only source of information used in compiling scientific reference indexes. Abstracts printed in other journals, especially foreign, in most cases consist of summaries from published papers. The summary should explain as adequately as possible the major conclusions to a non-specialist in the subject. The summary should contain from 100 to 300 words, depending on the length of the paper.

Publication of Paper

Disposition—All manuscripts should be addressed to the Institute of Radio Engineers, 33 West 39th Street, New York City. They will be examined by the Committee on Meetings and Papers and by the Editor. Authors are advised as promptly as possible of the action taken, usually within one month.

Proofs—Galley proof is sent to the author. Only necessary corrections in typography should be made. *No new material is to be added.* Corrected proofs should be returned *promptly* to the Institute of Radio Engineers, 33 West 39th Street, New York City.

Reprints—With the notification of acceptance of paper for publication reprint order form is sent to the author. Orders for reprints must be forwarded promptly as type is not held after publication.

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WASHINGTON	F. P. Guthrie	Thomas McL. Davis, (*Acting Secretary*), 4302 Brandywine St., N. W., Washington, D.C.

Raymond A. Heising
Member Board of Direction, 1929

Raymond A. Heising was born August 10, 1888 at Albert Lea, Minnesota. He received the E.E. degree from the University of North Dakota in 1912, and the M.S. degree from the University of Wisconsin in 1914. Since 1914 he has been a member of the technical staff of the Engineering Department of the Western Electric Company and of its successor, Bell Telephone Laboratories, specializing in radio telephony. He was at the transmitting end of the historical radio telephone experimental transmission between Arlington and Paris, Honolulu and Darien in 1915. During the war he worked on numerous war-time radio projects, and acted as instructor to technical men assigned by the War Department to the Western Electric Company laboratories. He has taken part in practically all of the American Telephone and Telegraph Company's recent radio projects. He has published numerous papers in this and other journals, and holds over fifty patents applying to practical radio development.

The Institute awarded Mr. Heising the Morris Liebmann Memorial Prize for 1921, and elected him a member of the Board of Direction in 1926. He is a Fellow of the Institute, has been Chairman of its Committee on Admissions, and a member of other of its Committees.

INSTITUTE NEWS AND RADIO NOTES

December Meeting of the Board of Direction

At the meeting of the Board of Direction of the Institute held in the Institute office on December 5, 1928 the following were present: Alfred N. Goldsmith, President; L. E. Whittemore, Vice President; Melville Eastham, Treasurer; John M. Clayton, Secretary; Arthur Batcheller, J. H. Dellinger, R. A. Heising, J. V. L. Hogan, and R. H. Marriott.

The following were transferred or elected to the higher grades of membership in the Institute: transferred to the Fellow grade: H. J. van der Bijl; transferred to the Member grade: P. H. Sohor and Sidney R. Wright; elected to the Member grade: M. W. Kenney, W. T. Runge, and Tadashi Fujimoto.

Ninety-three Associate members and eight Junior members were elected.

Appointment of Assistant Secretary

The Board of Direction of the Institute at its October meeting appointed C. J. Porter, of Buffalo, New York, Assistant Secretary of the Institute. For the past ten years Mr. Porter has been associated with the Westinghouse Electric and Manufacturing Company at Buffalo as radio specialist. He was a member of the organization committee of the Buffalo-Niagara Section and served as Secretary of that Section for two years. Mr. Porter assumed his duties with the Institute on November 1st. He will be mainly occupied in the handling of Section matters.

World Engineering Congress

The Institute has been requested by the American Committee of the World Engineering Congress, which is to be held in Tokio in October of 1929, to sponsor a paper on "The Trend of Radio Broadcasting and its Relation to National Solidarity." A Committee composed of Alfred N. Goldsmith, Chairman; B. A. Clark, B. Ray Cummings, D. G. Little, J. H. Dellinger, E. L. Nelson,

and Julius Weinberger has undertaken the preparation of a symposium paper which will be read at the Congress and subsequently published in the PROCEEDINGS.

Radio Stations of the World

The November 1928 issue of the PROCEEDINGS contained a list of frequency assignments throughout the world above 1,500 kc. Column three of page 1576 of this list is out of alignment. To give proper readings, move the first twelve lines of column three down one line, and move each line from "Drummondville P.Q." to the bottom of the page up one line.

Reprints of this list can be obtained free of charge by requesting Reprint No. 59. These reprints do *not* contain the above correction.

Chicago Section

The paper on "The Design of Transformers for Audio-Frequency Amplifiers with Preassigned Characteristics," by Glenn Koehler, published on page 1742 of the Decenber, 1928 issue of the PROCEEDINGS was presented before the April 20, 1928 meeting of the Chicago Section.

1929 Annual Convention

Plans for the 1929 Annual Convention to be held in Washington, D. C. on May 13–15 are being completed. Chairmen of the various committees have been appointed as follows: F. P. Guthrie, Convention Chairman; Thomas McL. Davis, Registration and Arrangements; Professor A. E. Kennelly, Fellowship; S. S. Kirby, Trips; F. P. Guthrie, Banquet; R. D. Heinl, Publicity.

Special arrangements are being made to entertain lady guests at this Convention. A Committee composed of Mrs. F. P. Guthrie, Mrs. J. H. Dellinger, Miss Mary T. Loomis, and Miss Elizabeth M. Zandonini has been appointed to arrange a number of features of special interest to the ladies present during the Convention.

The technical program plans call for a symposium meeting on the technical problems involved in radio legislation, and a similar meeting for a symposium on still and moving picture transmission by radio.

As the annual meeting of the U.R.S.I. consisting of a full day of technical programs follows on the 16th, the entertainment features of the Institute convention are being stressed. Members desiring to remain in Washington to attend the U.R.S.I. meeting will be cordially welcomed. At the U.R.S.I. meetings a large number of excellent radio papers are always presented.

Among the trips tentatively scheduled for the convention are inspection trips to the Naval Research Laboratory, the Bureau of Standards, Arlington Radio Station and the Tomb of the Unknown Soldier, and Mount Vernon.

The completed program of the convention will be announced in an early forthcoming issue of the PROCEEDINGS. Members are urged to set aside May 13 to May 15 for the 1929 Convention!

Dewey Decimal Classification

With this issue, on the title page of each paper will be found the Dewey Classification of each paper published in the PROCEEDINGS. This number appears as a footnote.

The index to the PROCEEDINGS for 1927 and 1928 will be published in the 1929 Year Book, arranged according to the Dewey Decimal Classification.

Members desiring further information as to the use of this method of classification and indexing are referred to "A Decimal Classification of Radio Subjects—An Extension of the Dewey System," Bureau of Standards Circular No. 138, which may be obtained from the Superintendent of Documents, Government Printing Office, Washington, D. C. for ten cents.

Edison Medal Awarded to Frank B. Jewett

The Edison Medal has been awarded by the Edison Medal Committee of the American Institute of Electrical Engineers to Dr. Frank B. Jewett, Vice President of the American Telephone and Telegraph Company, and President of the Bell Telephone Laboratories, for his contributions to the art of electrical communication.

The Edison Medal was founded by associates and friends of Mr. Thomas A. Edison, and is awarded annually.

U. S. Government Call Book

The June 30, 1928 edition of "Commercial and Government Radio Stations of the United States" is now available from the Superintendent of Documents, Government Printing Office, Washington, D. C. for fifteen cents.

In addition to a list of the land and ship radio stations, both commercial and governmental, the 1928 edition contains two lists of broadcasting stations, the first being the assignments prior to November 11, 1928 and the second the assignments subsequent to that date. The broadcast station lists are arranged alphabetically by call letters, alphabetically by states and cities, and numerically by wavelengths and frequencies.

Standard Frequency Transmissions by the Bureau of Standards

The Bureau of Standards announces its schedule of radio signals of standard frequencies for use by the public in calibrating frequency standards and transmitting and receiving apparatus. This schedule includes many of the border frequencies between services as set forth in the allocation of the International Radio Convention of Washington, which goes into effect January 1, 1929. The signals are transmitted from the Bureau's station WWV, Washington, D. C. They can be heard and utilized by stations equipped for continuous-wave reception at distances up to about 500 to 1,000 miles from the transmitting station.

The transmissions are by continuous wave radiotelegraphy. The signals have a slight modulation of high pitch which aids in their identification. A complete frequency transmission includes a "general call" and "standard frequency" signal, and "announcements." The "general call" is given at the beginning of the 8-minute period and continues for about two minutes. This includes a statement of the frequency. The "standard frequency signal" is a series of very long dashes with the call letter (WWV) intervening. This signal continues for about four minutes. The "announcements" are on the same frequency as the "standard frequency signal" just transmitted and contain a statement of the frequency. An announcement of the next frequency to be transmitted is then given. There is then a 4-minute interval while the transmitting set is adjusted for the next frequency.

Information on how to receive and utilize the signals is given in Bureau of Standards Letter Circular No. 171, which

may be obtained by applying to the Bureau of Standards, Washington, D. C. Even though only a few frequency points are received, persons can obtain as complete a frequency meter calibration as desired by the method of generator harmonics, information on which is given in the letter circular. The schedule of standard frequency signals is as follows:

RADIO SIGNAL TRANSMISSIONS OF STANDARD FREQUENCY SCHEDULE OF FREQUENCIES IN KILOCYCLES

Eastern Standard Time	Jan. 21	Feb. 20	March 20
10:00–10:08 P.M.	125	500	1500
10:12–10:20	150	600	1700
10:24–10:32	200	650	2250
10:36–10:44	250	800	2750
10:48–10:56	300	1000	2850
11:00–11:08	375	1200	3200
11:12–11:20	450	1400	3500
11:24–11:32	550	1500	4000

Institute Meetings

BOSTON SECTION

The Boston Section held a meeting in Cruft Laboratory, Harvard University, Cambridge, Massachusetts on November 16th. Dr. G. W. Pierce, Chairman of the Section, presided.

A paper, "Electrical Transmission of Pictures and Images," was presented by J. W. Horton, Chief Engineer of the General Radio Company.

Following the presentation of the paper the following members participated in its discussion: A. F. Murray, H. W. Lamson, A. E. Kennelly, H. J. Tyzzer, G. W. Pierce, L. F. Curtis and P. B. Bauer.

On December 12th a meeting of the Boston Section was held in Cruft Laboratory to hear a paper by Major Richard H. Ranger, of the Radio Corporation of America, on "Recent Developments in Photoradio."

It is hoped that both of these papers may appear in early issues of the PROCEEDINGS.

CANADIAN SECTION

A meeting of the Canadian Section was held on October 10th in the Electrical Building, University of Toronto. A. M. Patience, Chairman of the Section, presided.

B. F. de Bayley presented a paper, "A Direct Reading Audio-Frequency Bridge." Following the presentation the following members of the section participated in its discussion: Messrs. Patience, Smith, Meredith, Thompson, and others.

Fifty-three members of the Section and guests attended the meeting.

Cleveland Section

The second meeting of the 1928–29 season was held on November 23rd, in the auditorium of the Physics Building, Case School of Applied Science.

Chairman John R. Martin presided.

Dr. Dayton C. Miller, Ambrose Swasey, Professor of Physics at Case School of Applied Science, presented a paper "The Physical Characteristics of Music and Speech." The paper explained the early experiences of the author, which led him into the study of sound. Dr. Miller explained the development of the "phonodeik" to make visible the character of sound and waves. It consists of a glass diaphragm linked with a minute pivoted mirror. A beam of light is reflected by the movement of the diaphragm and then spread out on a screen by a revolving mirror.

A resumé of the underlying principles of sound and music was given, and the speaker explained and demonstrated tonal quality and wave composition by means of ten tuning forks.

The talk was supplemented with lantern slides, which were explained in detail. The "phonodeik" was demonstrated and projected a moving image of sound picture on a large screen in front of the audience. The wave shape produced by various musical instruments and the human voice was clearly shown.

Following the presentation of the paper a large number of persons participated in the discussion. There were about one hundred and thirty-five members of the Cleveland Section present and questions were asked at the end of the meeting.

New York Meeting

Dr. A. S. Eve, of McGill University, Montreal, Canada, came to New York on the evening of December 5th to present the paper "Reception Experiments in Mount Royal Tunnel," by Messrs. Eve, Steel, Olive, McEwan, and Thompson.

The paper appears in an early forthcoming issue of the Proceedings.

Following its presentation the following members took part in the discussion: A. S. Eve, Alfred N. Goldsmith, R. H. Marriott, Haraden Pratt, J. H. Dellinger, G. W. Kenrick, and others.

One hundred and seventy-five members and guests attended the meeting.

The January 2nd, 1929 meeting in New York will be addressed by Dr. V. Zworykin, of the Westinghouse Electric and Manufacturing Company, on the subject of "Facsimile Picture Transmission."

Philadelphia Section

On November 23rd a meeting of the Philadelphia Section, held in the Franklin Institute, was addressed by G. W. Kenrick. The paper was entitled, "The Heaviside-Kennelly Layer and Its Relation to Radio Transmission Phenomena."

The paper reviewed the historical development of radio transmission theory and considered evidence for the existence of a conducting layer. Group time and phase retardation measurements in determining the virtual height of the layer as a function frequency and angle were described. New group time experiments which show the diurnal variation of the layer and the effect of a magnetic storm were presented. The paper also described the methods of determining the ratio of "real" to "virtual" height of the layer from group time and phase retardation experiments, and the application of the results thus determined to a study of the variation of electronic and ionic density in the upper atmosphere as a function of height was mentioned.

The meeting was presided over by J. C. Van Horn, Chairman of the Section. Thirty-five members of the Section were present.

Pittsburgh Section

A meeting of the Pittsburgh Section was held on November 20th in the Fort Pitt Hotel, Pittsburgh. L. A. Terven, Vice-Chairman of the Section, presided.

V. D. Landon, of the Westinghouse Electric and Manufacturing Company, presented a paper on "Radio Installation for Apartment House Use." The paper described an antenna distribution system on radio frequencies for apartment houses and similar structures. The system is composed of a radio-frequency amplifier and a distributing coupling circuit. A single antenna approximately 30 feet high and 80 feet long is used with the system in conjunction with a separate frequency amplifier in each group of ten or less receivers. Each receiver

has its own distribution coupler. Detailed theory of the system was explained and worked up from formulas.

Following the presentation of the paper, Messrs. Sutherlin, Sunnegrin, McKinley, Allen, and Terven participated in its discussion.

Twenty-four members of the Section attended the meeting.

Washington Section

On November 8th a meeting of the Washington Section was held in the Continental Hotel, 1 Capitol Street, Washington, D.C. F. P. Guthrie, Chairman of the Section, presided.

Warren B. Burgess, of the Naval Research Laboratory, presented a paper on "Radio Compass in Theory and Practice."

Following the presentation of the paper, the following took part in its discussion: H. G. Dorsey, G. D. Robinson, D. G. Howard, Colonel Parrott, F. P. Guthrie, T. Parkinson, R. B. Stewart.

Forty-six members and guests attended the informal dinner preceding the meeting and sixty-five members attended the meeting.

On December 13th a meeting of the Washington Section will be held in the Continental Hotel. Dr. E. O. Hulburt, of the Naval Research Laboratory, will deliver a paper on "Radio Transmission and Magnetic Storms."

Committee Work

Committee on Sections

A meeting of the Committee on Sections was held in the Institute Office on November 16th. The following were present: Donald McNicol, Chairman; Arthur Batcheller, and C. J. Porter, Assistant Secretary.

The Committee studied the proposed revised constitution, which is to be submitted to the Institute membership for approval in the near future, with a view to making necessary recommendations to the Board of Direction regarding portions of the Constitution affecting the Institute Sections.

Correspondence looking to the formation of Institute Sections in Schenectady, St. Louis, Milwaukee, Minneapolis, and Cincinnati was reviewed.

Committee on Admissions

The Committee on Admissions met on December 5, 1928 in the Institute office. R. A. Heising, Chairman, E. R. Shute, and F. H. Kroger were present. The Committee considered six applications for transfer or election to higher grades of membership in the Institute.

Personal Mention

L. E. Hayslett has left Kenmore, New York, to become Inspection Engineer of the United Reproducers Corporation of Rochester, New York.

A. C. Matthews has left Schenectady, New York for Chicago where he is now employed as radio engineer with the Stewart Warner Corporation.

W. E. Miles has been transferred from the Naval Communication office, Navy Yard, Boston to the Naval Radio Traffic Station, Bar Harbor, Maine.

R. V. Beshgetoor, formerly with the General Electric Company at Schenectady is now in the Engineering Products Division of the Radio Corporation of America in New York City.

Edgar H. Felix has joined the staff of the National Electrical Manufacturers' Association, specializing in radio problems. Mr. Felix is on the Institute Committee on Meetings and Papers.

W. W. Lindsay, Secretary of the Los Angeles Section of the Institute, is now associated with the Movietone Department of William Fox Studios at Hollywood, California, as research engineer.

William F. Diehl, who for the past ten years has been connected with the A. H. Grebe Company as Chief Engineer, recently joined the staff of the Radio Division of the Victor Talking Machine Company, of Camden, New Jersey.

Maurice Berger, formerly with the Radio Corporation of America at New York City is now associated with the Electrical Research Laboratories, Incorporated, of New York City. Mr. Berger has been a member of the Institute's Committees on Membership and Sections for several years.

David Casem, for the past five years radio editor of the New York Telegram has been appointed director of the publicity bureau of broadcasting station WOR at Newark. Mr. Casem has served on the Institute's Commitee of publicity for a number of years.

Proceedings of the Institute of Radio Engineers
Volume 17, Number 1 *January, 1929*

GEOGRAPHICAL LOCATION OF MEMBERS ELECTED DECEMBER 5, 1928

Transferred to the Member grade

California	Los Angeles, 800 North Spring Street	Sohor, P. H.
England	Shipley, Yorkshire, 14 Bankfield Drive	Wright, Sidney R.

Elected to the Member grade

Illinois	Elmhurst, 265 W. North Avenue	Kenney, M. W.
Germany	Berlin, Wittenau, Robertstr	Runge, Wilhelm T.
Japan	Tokyo, Setagaya, 429 Taishido	Fujimoto, Tadashi

Elected to the Associate grade

Arkansas	Blytheville, 304 Davis Avenue	Lintzenich, C. L.
California	Glendale, 408 Wing Street	Shomler, H. B.
	Hollywood, 1030 N. Western Avenue	Finstein, Paul
	Hollywood, 1345 North New Hampshire Avenue	Sarver, Frank M.
	Los Angeles, 4503 Paulhan	Andersen, H. W.
	Los Angeles, 1444 So. Norton Avenue	Buffinger, William
	Los Angeles, 1441 W. 51 Place	Hill, Alfred LeRoy
	Los Angeles, 1050½ Cloverdale	Stevens, Sterling M.
	Sterling City	Overton, D. C.
	Stockton, 1520 N. Eldorado Street	Holt, Pliny E.
Georgia	Atlanta, c/o General Electric Co., P.O. Box 1698	Bussey, H. E.
	Atlanta, 1331 Lucile Avenue, S. W.	Wallace, Lawrence T.
	Columbus, c/o Columbus Electric and Power Co.	Farris, Herbert Talley
Illinois	Chicago, 100 W. Monroe St.	Fillmore, Harry Philip
	Chicago, 2247 Calumet Avenue	Hauser, Albert
	Chicago, c/o R. C. A., 100 W. Monroe Street	Kennedy, W. J. B.
	Chicago, 1544 North Dearborn	Nourse, Philip R.
	Chicago, 4430 Clifton Avenue	Turner, C. G.
	Dixon, 521 McKenney Street	Hall, Howard J.
	Kewanee, 219½ West Second Street	Larson, Clifford L.
	Urbana, Dept. of Elec. Eng., University of Illinois	Hershey, Arthur W.
Indiana	Indianapolis, 1036 Eugene Street	Byers, Russell R.
	Valparaiso, 402 Monroe Street	Alexander, Leslie Alpheus
	Valparaiso, 555 So. College Avenue	Imler, Glenn M.
Iowa	Hale, Box 29	Kruse, Gerald D.
Louisiana	Baton Rouge, 830 North Street	Webre, Andrew S.
	New Orleans, 3624 Magazine Street	de Otter, G.
	New Orleans, 1222 Eagle Street	Pasquet, Jean E.
	New Orleans, 2655 Canal Street	Rabito, A. Paul
Massachusetts	Cambridge, Massachusetts Institute of Technology	Barrow, W. L.
	Cambridge, 28 Gorham Street	Shen, Pinlu
	Cambridge, General Radio Co.	Worthen, Charles E.
	North Attleboro, Old Post Road	Barrett, Kerman R.
	Roxbury, 38 Atherton Street	Collins, Lewis R.
	Swampscott, 12 Humphrey Terrace	Humphrey, Stanley M.
Michigan	Detroit, 295 Ferry Street	Line, F. M.
Minnesota	Minneapolis, Francis Drake Hotel	Brooks, Kenneth E.
	St. Paul, Federal Bldg., Room 413	Heiser, Edwin S.
New Jersey	Boonton, 804 Main Street	Pittenger, Arthur W.
	Hackensack, c/o Gotham Electric Sales Corp., 272 Main St.	Slocum, K. W.
	Jersey City, 96 Duncan Avenue	Palmer, C. Walter
New York	Brooklyn, 289 Henry Street	Kearney, L. E.
	Brooklyn, 446 Ocean Avenue	Thomas, Howard H.
	Brooklyn, 167 Clinton Avenue	Welker, Paul L.
	Brooklyn, 2526-85th Street	Yonofsky, Harry
	Buffalo, 79 Roanoke Parkway	Beyer, Glen R.
	Buffalo, 1204 Kensington Avenue	Carmody, Raymond P. M.
	Buffalo, 62 Mandan Street	Deane, Harold A.
	Buffalo, 291 South Elmwood Avenue	Flutka, Ralph M.
	Buffalo, 778 Washington Street	Lord, Harry Raymond
	Buffalo, 116 Hartwell Road	Morrison, John F.

	Buffalo, 131 Peabody Street	Pritchard, John A.
	Buffalo, 176 Laurel Street	Wright, George A.
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	New York City, 72 Cortlandt Street, Room 301	Moore, E. B.
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	Tonowanda, R.F.D. No. 1	King, Francis N.
Ohio	Alliance, 209 E. Prospect Street	Mitchell, H. J.
	New Philadelphia, 252 Second Street, N. W.	Murray, Charles J.
	Ravenna, Box No. 4	Rettig, Floyd A.
	Youngstown, 106 Carroll Street	Wilkins, Bernard T.
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For Election to the Associate grade

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	Mobile, P. O. Box 801	Helt, Scott
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Part II

TECHNICAL PAPERS

Proceedings of the Institute of Radio Engineers
Volume 17, Number 1 *January, 1929*

A DIRECT READING RADIO-FREQUENCY METER*

By
R. C. Hitchcock
(Research Laboratory, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Penna.)

Summary—*The method used is the well known one of reading a radio frequency by measuring the beat note produced with a calibrated crystal oscillator.*

A new type of direct reading audio-frequency meter having a scale of 2.0 to 4.5 kc per second makes the device automatic.

The meter scale divisions are 0.1 kc apart, and under reasonable conditions, the accuracy of the reading is of this order.

THERE are two classes of meters which are usually used to measure radio frequencies. The first is the tuned circuit absorption type. With this type the radio source must be coupled closely enough to supply the necessary energy to the meter. The first wavemeters of this type used a single variable condenser shunted by a single coil and some kind of resonance indicating device. Well made tuned circuit meters are reliable to about 2.5 kc per second in the present broadcast band.

The Bureau of Standards Frequency Meter Type B was the next step in the absorption type of meter, the range being narrowed with a corresponding increase in precision by shunting a small variable condenser across a large main fixed condenser. Two series coils were used, the smaller one being unwound during calibration, so that the wave to be measured came at the mid point of the small variable condenser.

Recently a still more precise narrow range frequency meter has been placed on the market.[1] This meter has been designed to cover 0.3 per cent of a radio station's frequency with the use of a single control. At 1500 kc per second this means that the whole range of the meter is 4.5 kc per second. The manufacturer specifies 10 scale divisions per kc, and guarantees for six months a precision of 500 cycles per second when the instrument is kept within ± 5 deg. F of the calibration temperature given on the chart. If a more accurate meter of this type is desired, the whole unit might be calibrated in a temperature-controlled oil bath. Stand-

* Dewey decimal classification: R210. Original manuscript received by the Institute, October 16, 1928.

[1] Frequency meter, type 532, General Radio Co.

ard oscillator crystals are usually temperature-controlled, and a standard tuned circuit would be more accurate if temperature control were employed. An ingenious resonance indicating device makes the instrument much more sensitive than previous meters of the absorption type.

Oscillator as a Frequency Meter

The second type of frequency meter is a calibrated oscillator. The beat note between the oscillator and the desired source is measured and applied to the known value of the oscillator frequency. This type of meter has the advantage that it can be operated some distance from the radio source to be measured.

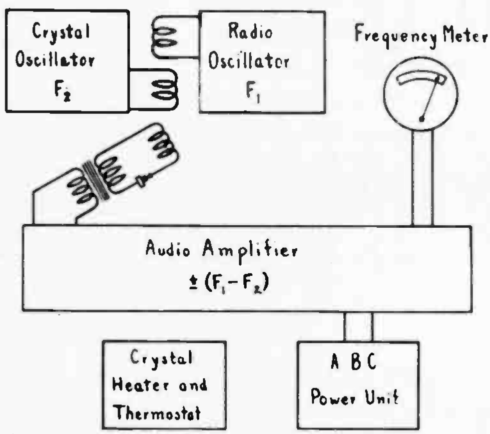

Fig. 1—Schematic Diagram.

By using suitable audio amplification, several miles may separate the radio source and the standard measuring oscillator. It is the purpose of this paper to describe a meter of this second type, which can give a radio frequency directly on a meter scale.

It is realized that the general scheme of using a beat method of calibrating one frequency from another is a standard one, and that harmonics of a standard oscillator are also widely used for calibration purposes. However, as the use of an indicating audio-frequency meter has received little attention, the circuit and various details will be given here.

Standard Crystal Oscillator

This meter being a beat frequency indicating device, it is essential that an accurately calibrated crystal oscillator unit be

employed. Such units have been described[2] and will not be discussed here. In the schematic drawing of Fig. 1 the crystal oscillator unit generates the radio frequency F_2. The source of radio frequency to be measured F_1, is loosely coupled to F_2 and the beat frequency

$$f = \pm (F_1 - F_2) \tag{1}$$

is passed on to the audio amplifier from a detector circuit which is tightly coupled to the crystal oscillator. This beat frequency

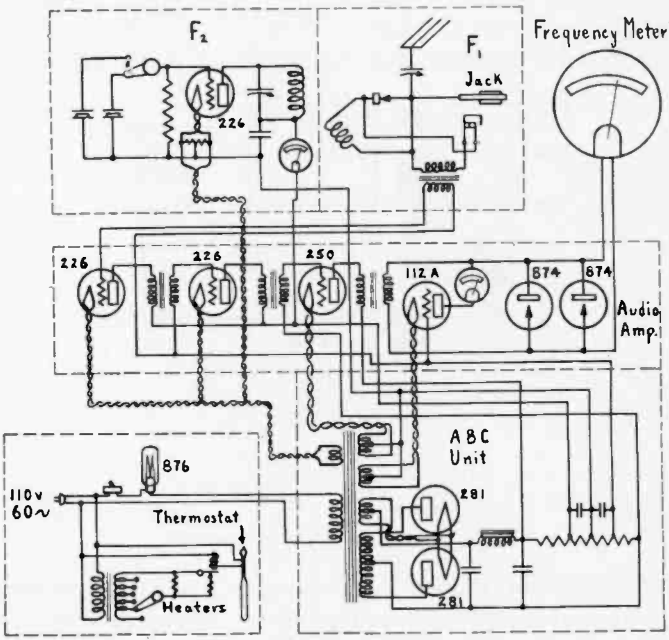

Fig. 2—Wiring Diagram.

after being amplified is fed to the indicating audio-frequency meter. This meter can be calibrated either in terms of the audio frequency of the beat (Fig. 3), in which case the meter reading is applied to the calibrated crystal frequency to determine the frequency of the source; or the scale can be calibrated directly in radio frequency (Fig. 4), having the same kilocycle range as the audio frequency.

The special audio-frequency meter which made this device

[2] Crossley, Proc. I.R.E., 15, 9; January, 1927. Worrall and Owens, Proc. I.R.E., 16, 778; June, 1928.

possible[3] has a useful scale range of 2.0 to 4.5 kc per second spread over an arc of 90 deg. This meter is of the tuned circuit type, its impedance being three times as great at the center of the scale as at the ends. To minimize this effect on the rest of the audio circuit, a 2:1 stepdown transformer is placed between the UX-250 tube and the meter. The complete wiring diagram is given in Fig. 2. The voltage amplifiers are UX-226 tubes, and the crystal oscillator also uses a UX-226 tube. Across the frequency meter are placed two UX-874 voltage regulator tubes to improve regulation, as will be mentioned later.

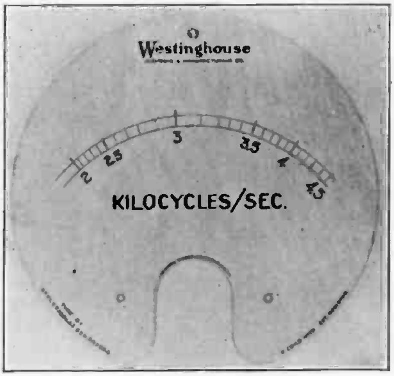

Fig. 3

Voltage Regulation at the Meter

The reading of the audio-frequency meter is dependent to some degree on the voltage supplied. Fig. 6 gives the characteristic curve of the meter when the applied voltage is kept at 60 volts. Where the slope is least, in the middle of the scale, the readings will be most accurate. The arbitrary scale plotted as the abscissa is a uniform one which was spaced along the arc of the meter scale for experimental purposes. Due to the low impedance at the ends of the scale it was not possible, without building another special amplifier, to maintain the voltage above 60 throughout the whole range. Hence this curve of Fig. 6 at 60 volts was taken as a basis of comparison to show the effects of changing voltage. Fig. 7 gives the deviation in cycles per second from the values of Fig. 6 for 70, 80, and 90 volts applied to the

[3] Designed by Mr. B. E. Lenehan, Supply Eng., W. E. and M. Co., Newark, N. J.

meter. It will be noted that the maximum deviation is less than 200 cycles per second with voltages from 60 to 80. The use of two UX-874 tubes in parallel across the meter was found to keep the voltage to 68 ± 5 volts, therefore the variations due to voltage, over the range 2.0 kc to 4.0 kc are of the order of ± 50

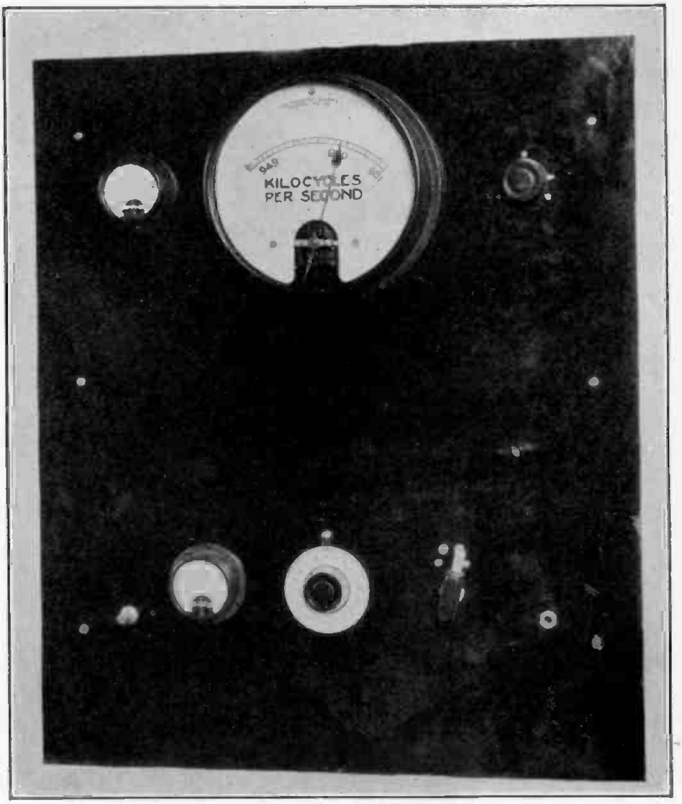

Fig. 4

cycles per second.[4] Closer regulation of voltage is hardly justifiable in view of the other factors affecting the frequency; the crystal temperature, oscillator tuning and variations in coupling to the source. A more nearly constant voltage for precision work could be obtained by using a manually controlled resistor across the meter. Such a resistor was the first scheme used to keep the

[4] The meter indication changes slightly with room temperature variations.

applied meter voltage nearly constant. The resistor knob is shown in the upper right of Fig. 4. The alternating voltage across the meter can be read by a calibrated milliammeter in the plate circuit of a UX-112A tube. The connection is given in Fig. 2. After inserting the two UX-874 regulator tubes, the manual

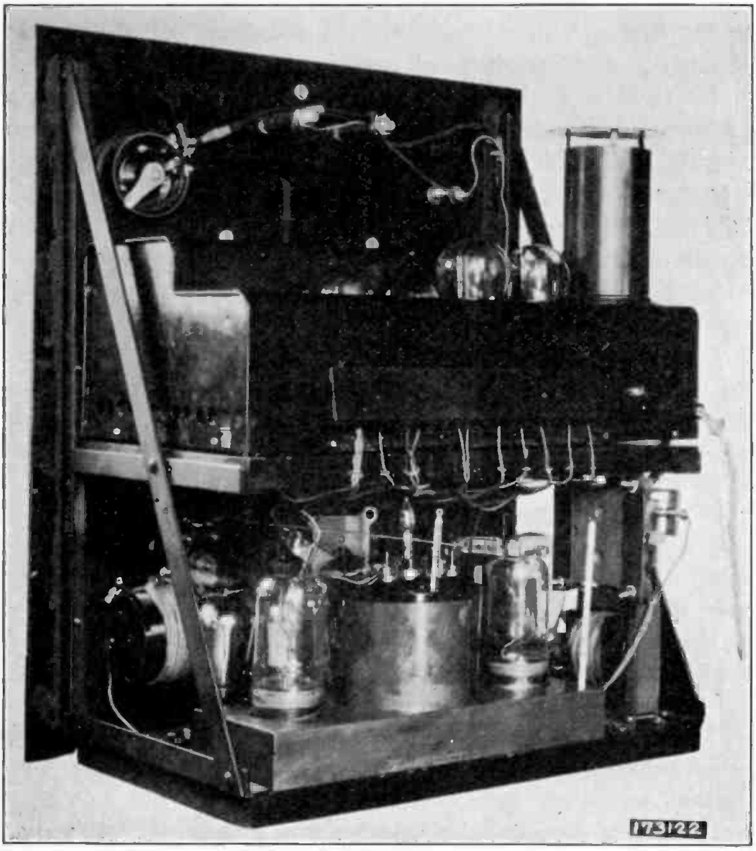

Fig. 5

resistor was seldom used except for fine adjustments. For this reason it was not included in Fig. 2.

It is not necessary that the fundamental frequencies of the standard and the source to be measured should be within an audio frequency of each other, as beats may be obtained between harmonics. For instance, a 50 kc per second standard crystal can be used to read station frequencies close to $50n$ kc per second

where n is an integer between 11 and 30 for stations in the broadcast band of 550 to 1500 kc per second. To do this, f, the beat frequency, should be within the range of the frequency meter, the relation between F_1, f, and the 50 kc standard being given by (2)

$$f = \pm (F_1 - 50n) \tag{2}$$

The proper harmonic of the standard will beat with the station frequency and the reading will appear on the meter scale, which can be translated directly to a radio-frequency value. If a high harmonic is used, sufficient amplification should be provided to supply the meter with the required voltage.

In measuring a properly designed crystal-controlled radio-frequency source with this frequency meter it is quite unlikely that the change should ever be more than a fraction of a kilocycle, which would be indicated by the meter. But if a tuned circuit master oscillator is being measured it is just possible that its frequency might change by such an amount that the audio beat would be the same as when the radio frequency was at its correct value. In this case, the frequency meter would indicate the proper beat, but on the other side of the standard crystal oscillator.

To illustrate, suppose the frequency of the checking crystal to be 947 kc in order to check a radio station at 950 kc, the frequency assigned to KDKA in June 15, 1927. The frequency meter would also read this beat, 3 kc, if the station frequency were 944 kc, which would be 6 kc from the assigned value. This double value is indicated by the plus or minus signs of (1) and (2). To eliminate this ambiguity two crystal standards can be used; to check a 950 kc station, crystals of 947 and 953 kc per second would serve. Then for the case cited, the second crystal standard would not give its check at its regular place of 3 kc, when the low frequency of 944 kc was impressed, but would tend to show 9 kc, and although this value is off scale for the frequency meter, the operator can tell by the action of the milliammeter that either a low or a high frequency is being measured. That is, the impedance of the meter being low at both ends, the low milliammeter reading would mean a low impressed voltage on the meter, and in turn would indicate a frequency not on the scale of the meter. Another way of eliminating the ambiguity of the double sign would be to use two crystal standards on the same side of the measured frequency, for instance 947 kc and

948 kc. Then for a 950 kc station the correct reading would be 3 kc for the first, and 2 kc for the second. Should the source change its frequency to 944 kc, the first standard would indicate its usual 3 kc, but the second would now show 4 kc definitely locating the value of radio frequency at 944 kc. The two crystals used in the meter are shown in Fig. 6 mounted in the copper-glass tubes described by the author in an earlier paper.[5] A large copper block serves to conduct heat from the thermostatically controlled chamber in the center. The wiring details are incorporated in Fig. 2 at the lower left. The main heater is left on all the time, while the auxiliary one is turned on and off by a

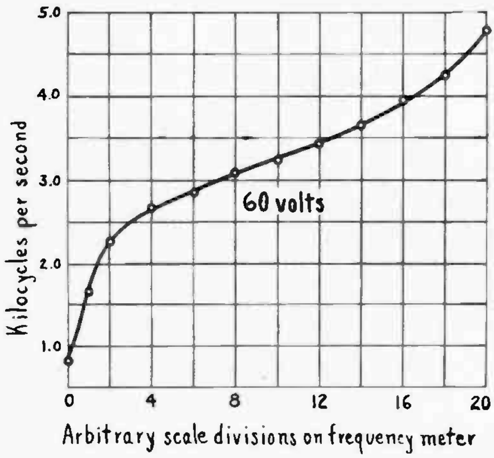

Fig. 6

contact making thermometer and suitable 110-volt relay. The switch lever and two points for selecting either of the two standard crystal oscillators are shown in Fig. 4 at the lower right.

When the meter is being used to read a radio station frequency while a program is being broadcast, the crystal detector supplies the program, as well as the beat frequency, to the audio amplifier. If the program consists of a man speaking at a frequency of a few hundred cycles per second and the beat is, say 4 kc per second, the frequency meter will momentarily take up a position between these two values. The higher frequency of a woman's voice will not change the reading so much. However, there are always

[5] R. C. Hitchcock, Proc. I.R.E., 15, 902; November, 1927.

momentary pauses in a program when the beat frequency will be the predominant one, and the meter can always be read with a precision better than one scale division.

If only a high-frequency beat is to be used, a high pass filter has been used to cut out the lower voice frequencies satisfactorily. This limits the use of the meter to its high end, but reduces the variations of the pointer when indicating the beat.

In the original setup of this frequency meter, KDKA is measured whenever it is on the air, a relay being automatically operated by the energy collected by a tuned antenna circuit. The meter as ordinarily balanced has an equilibrium position at about the center of the scale. This was not desired when the

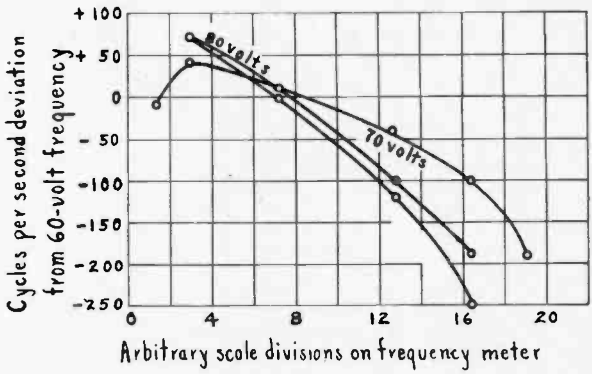

Fig. 7

scale was calibrated in radio frequency, as it intimated that the station was on the air at all times, and indicated a fictitious frequency whenever the station was not being operated. To make the meter pointer move to the extreme left, a back contact was added to the relay operating the amplifier, so that when the station went off the air, the relay opened the power circuit to the amplifier and connected the 110-volt 60-cycle supply through a 2 μf condenser across the frequency meter. This drew the meter pointer off scale to the left whenever the station was not on the air.

To make the meter available for other purposes than station frequency checking, a jack has been placed as shown in the wiring scheme of Fig. 2 and photograph of Fig. 4 so that audio energy within the range of the meter may have its frequency measured, and the crystal oscillator automatically disconnected by inserting a plug.

Warning Devices for Frequency Changes

As this meter is probably accurate to better than 200 cycles per second under adverse conditions, and as the Federal Radio Commission specifies a maximum deviation of 500 cycles per second from an assigned broadcast frequency, it is possible to devise warning instruments which will operate when the pointer of the frequency meter touches light contact members placed

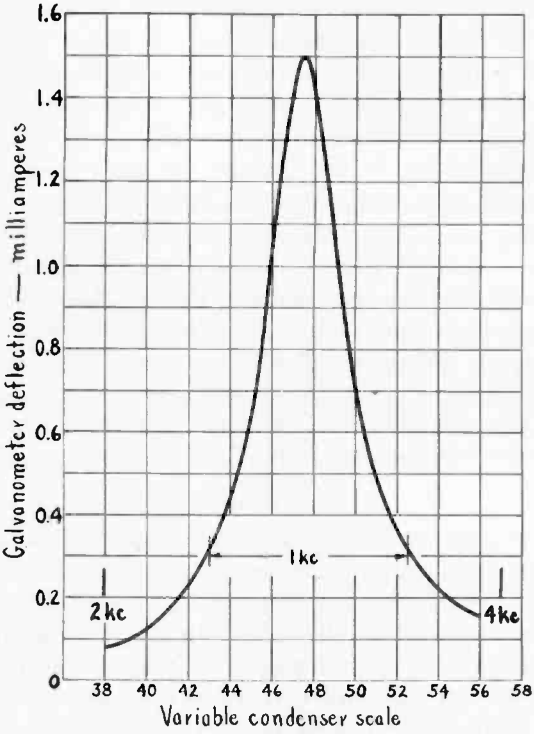

Fig. 8

within the allowable limits of frequency deviation. A grid glow relay[6] which operates with a fraction of a microampere would serve to operate heavier current relays to sound suitable alarms when the frequency changed by a predetermined amount.

Parallel Tuned Circuit

Another indicating device which could replace the audio-frequency meter would be a parallel resonant circuit. This circuit would be tuned to the beat frequency f, and a meter

[6] D. D. Knowles, *Elec. Jour.*, 176, April, 1928.

showing the change in oscillating current used to read frequency changes. A typical curve with a peak at 3 kc is shown in Fig. 8. A 6-mh coil and variable condenser of 0.05 μf across a fixed one of 0.5 μf was used. A loosely coupled pick-up coil, detector, and d.c. milliammeter gives the resonance indication without adding to the resistance of the resonant circuit.

By using resistance coupled amplification any beat frequency could be measured by this scheme, although accuracy is greater for lower beat frequencies. A tuned circuit meter when used to measure an audio beat is more accurate than another tuned circuit meter with the same sharpness of resonance,[7] at radio frequencies, by the ratio of the radio to the audio beat frequency. This assumes the use of a good crystal oscillator standard for producing the beat frequency.

An advantage of this latter scheme over the frequency meter is that the standard could be chosen several kilocycles away from the frequency to be measured, so that the operator could be sure that the frequency was either higher or lower than that of the standard oscillator. This would permit the measuring of several radio frequencies with a single crystal standard by plugging in suitable tuned audio circuits. This also means that the precision would be reduced, as the beat frequency was increased.

Conclusion

This frequency meter is automatic, requiring no manipulation of controls to read a radio frequency. Its scale is spread out so that the frequency divisions are 0.1 kc apart. By using several standard crystals, the meter can read several frequencies and their harmonics, with a precision depending in part on the calibration of the standard crystal. A final advantage is that the meter need not be placed as close to the source as a tuned circuit meter.

Of course the meter described is more complex than a tuned circuit meter, but it is felt that a meter of this type would be of service to radio stations and laboratories. Simple relay schemes can be devised to turn on the meter whenever the radio frequency is on, requiring a minimum of attention.

The writer wishes to express his thanks to Mr. V. E. Trouant for his helpful suggestions and for his data on the parallel tuned circuit; to Mr. E. B. Landon for his cooperation at KDKA; and to Mr. J. C. Batchelor for much of the experimental work connected with this frequency meter.

[7] Circular of the Bureau of Standards, No. 74, Ed. 1918, pp. 36–37.

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ON .NATION OF THE OPTIMUM RADI- FOR HORIZONTAL ANTENNAS*

By

. Meissner and H. Rothe

ry of the Telefunken Company, Berlin, Germany)

tandard of (directional) radiation at 15 meters was g of a vertical half-wave antenna placed one-half wave ibly excited, placed in front of a reflector consisting of five tly more than one-half wave long on a parabolic surface of welength. This was found to give directional characteristics maximum of field strength twice that of the simple antenna r.

olic reflector and radiating system rotatable about a horizontal dicular to the line to the distant station were then constructed near he antenna at the focal axis of the paraboloid was one wave long, er wavelength from the parabola apex; and the parabolic reflector ne wavelength opening and consisted of 9 wires along the paraboloid pproximately a half-wave long.

he entire system was rotated while reception audibility measurements were made at Buenos Aires, a 2-kw transmitter being employed. The horizontally aimed system was found most effective. This held for both 15 and 20 meters. Similar results were obtained for reception on directional antennas. The conclusion is drawn that horizontal short-wave radiation is most desirable.

In our first experiments with horizontal antennas in August and September, 1925,[1] it was found necessary for the best technical utilization of the effect of horizontal antennas to concentrate the antenna radiation at the angle most advantageous to reception. At first we tried to obtain this by combining several horizontal antennas in a horizontal plane (the antennas were $\lambda/2$ apart) with the corresponding surface of reflectors $\lambda/4$ under them. The various antennas had to be excited with a definite phase difference between them for adjustment of a certain angle of emission. We had no difficulty in setting the different phases among the antennas, but we had no phase indicator to show just what phase was actually present in each antenna. We were, therefore, compelled to return to the simple horizontal antenna system and to concentrate radiation by means of a parabolic reflector. The first parabolic reflector was made of sheet copper for a wavelength of 11 meters. When turn-

* Dewey decimal classification: R125.6. Original manuscript received by the Institute, June 29, 1928. Translation received July 19, 1928.

[1] A. Meissner, "On Space Radiation," *Jahrbuch fuer drahtlose Telegraphie*, 30, p. 77; *Telefunken-Zeitung*, October, 1927.

ing the reflector for this wavelength, we found the optimum angle at 38 deg. and a second, somewhat less favorable angle at 80 deg. The reflector could only be depressed to an angle of about 35 deg. below the horizontal. We, therefore, set up a fixed reflector system, which could be remodeled easily for radiations of 0 deg., 10 deg., 20 deg., and 30 deg., for purposes of comparison with the rotatable reflector. The comparison reflector was a wire reflector. Tests had in the meantime shown that the sheet could be replaced by wires; the wire reflector was even somewhat superior to one made of sheet. At the test wavelength of 11 meters and at angles of radiation of 0 deg., 10 deg., and 20 deg., the fixed reflector did not show any definitely noticeable difference as compared with the metal reflector at 38 deg.

The ensuing tests were to determine the optimum radiation angle for operating wavelengths; wavelengths above 15 meters.

Tests with the 20-meter Wave

The existing reflector was then enlarged for the longer wavelengths. At each end another arch was added at a distance of 5 meters to the three parabolic wooden arches supporting the reflector surfaces, so that an antenna two half-waves long and oscillating in phase could be built in for a wavelength of 20 meters. The antenna was hung in the focal line of the reflector (5 meters from the apex of the parabola—width of the parabola opening: 20 meters). The parabolic surface was formed by 9 reflector wires (9.60 meters long). Preliminary experiments had determined the optimum length of the reflector wires as well as the concentration of radiation obtainable with the reflector system employed. This was done with a fixed vertical parabolic reflector system with an opening 15 meters wide and a focal length of about 3.75 meters which corresponded to the horizontal rotatable reflector. The tests were made at a wavelength of 15 meters. The transmitting antenna was vertical, $\lambda/2$ long, with its center $\lambda/2$ above the earth excited at the lower voltage loop by a double line system $4/\lambda$ long wires 15 cm apart. One of the energy supply lines ended $\lambda/4$ over the ground, while the antenna, $\lambda/2$ long, was directly connected to the other line. In the investigation of the influence of the number and tuning of the reflector wires it was found that for a parabola with an opening of λ width, five reflector wires suffice and that an increase of the number of wires does not improve concentration. When

changing the length of the reflector wires one gets a broad maximum of field intensity in front of the reflector. The optimum value lies at a natural wavelength of the reflector wires approximately 5 per cent longer than half the operating wavelength. The tests were made at a distance of about 10 wavelengths with the aid of a tuned tube receiver. In Fig. 1 the numerical values are proportional to the field intensity. We see that the concentration is comparatively broad. The field intensity in front of the reflector is practically constant throughout an angle of approximately 40 deg.

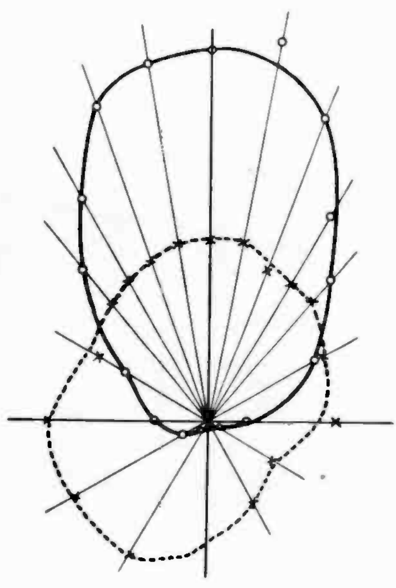

Fig. 1—Radiation Diagram for the Optimum Adjustment of the Reflector.
——————with reflector
- - - - - - without reflector

At the maximum it is about twice as large as the field intensity of the vertical antenna alone, represented by the broken line. The dissymmetry of this curve is probably due to the nearness of the antenna system. Within six minutes the reflector could be turned from 40 deg. above the horizontal in the direction of Buenos Aires through 90 deg. to 40 deg. above the horizontal in the other direction, away from the receiver. The transmitter was a self-oscillating push-pull vacuum-tube transmitter fed with 500-cycle alternating current. The antenna was connected through a double line (wires 12 cm apart) 30

meters long. Standing waves in the line were avoided by means of a suitable coupling of the energy supply line to the antenna. The power in the antenna was about 2 kw. Buenos Aires measurements were made by the shunted-telephone audibility meter method. The angle tests were made on two days (Nov. 30 and Dec. 1, 1927) between 11 A.M. and 12 noon and between 6 P.M. and 9 P.M. by means of the continuous turning of the reflector within the above-mentioned angles in the space of six minutes. A total of 38 observation values was obtained. The mean of the reception results corresponds approximately to the curves of

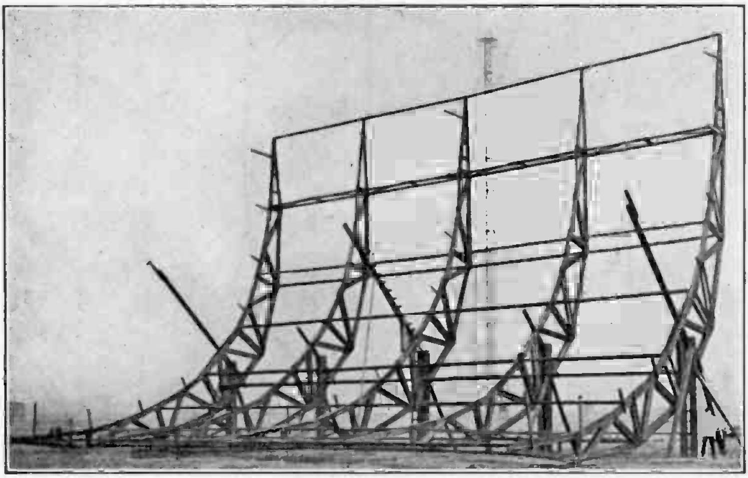

Fig. 2—Rotatable Reflector in the Setting for A Radiation Angle of 40 Degrees.

Fig. 4. The unbroken line represents the tests on the first day, the broken line those on the second day. The reception results on both days show that the optimum radiation of the rotatable reflector takes place at its smallest angle: 40 deg.–50 deg. In order to see whether even smaller radiation angles than 40 deg. are still better, we again arranged a fixed reflector system alongside the rotatable one and exactly similar to it. Within an hour it could be easily set at any angle from 0 deg. to 40 deg. The fixed reflector was always compared with the optimum setting of the rotatable reflector (40 deg.). The first thing we noticed was that for the same radiation angle the fixed reflector was always superior to the movable one, about in the ratio 1.3 to 1. This was perhaps due to the fact that there were losses in the wooden

parts of the rotatable reflector system. Probably it is also due in part to the circumstance that the antenna of the fixed system was somewhat higher ($h=11$ meters) than that of the rotatable reflector ($h=8$ meters).[2] The table gives the values for the fixed and rotatable reflectors at various settings of the fixed reflector:

TABLE I

Rotatable reflector	40 deg.	1
Fixed reflector	40	1.3
" "	30	1.5
" "	20	2.0
" "	10	2.5
" "	0	5.0

This shows that the radiation angles between 0 deg. and 20 deg. are superior to the radiation angles of the rotatable reflector between 40 deg. and 50 deg. The fact that the angle 0 deg. is so particularly favorable is possibly due to the fact that the very dispersed radiation of the reflector (see Fig. 1) is concentrated more strongly by the reflecting influence of the earth. In general, in the emission of horizontally polarized waves the influence of the earth on the upward bending of the rays is apt to be very great.[3]

Tests with the 15-meter Wave

The reception results with the rotatable reflector at $\lambda=15$ meters gave the same results as at the 20-meter wave. The rotation tests were made on December 16th and 17th, 1927, between 12 noon and 3 P.M., Central European time. The plotted results obtained by turning the reflector were altogether like those with the 20-meter wave (Fig. 4). The reception maximum lay at 40 deg. Here again the rotatable reflector was compared with the fixed reflector at the settings 0 deg., 10 deg., and 20 deg. The reception values in this comparison were not as definite as with the 20-meter wave, because the method of audibility measurement at the receiving end had been changed and was unreliable.

[2] With a width of the parabola opening equal to the wavelength, the fixed horizontal antenna with parabolic reflector could not be hung lower than 11 meters, on the other hand the antenna of the rotatable reflector could not be arranged higher than 8 meters without considerably increasing the cost of the system. Comparative tests of reception between a simple horizontal antenna hung at a height of 8 m and a similar antenna hung at a height of 11 m gave differences smaller than 1:2. When used in combination with the reflector, the difference may be estimated to be smaller than 1:1.5.

[3] As a result of tests of simple vertical dipoles hanging at various heights T. L. Eckersley had assumed as early as 1926 that for vertical antennas the horizontal radiation of the transmitter was most advantageous. (See *Jour.* I.E.E., 65, 601, 1927.)

But the observed values were clear enough to show that reception at horizontal emission was at least twice as good as at a radiation angle of 40 deg. These conclusions were confirmed by tests with the regular operating transmitter AGA (wavelength 15 meters); by changing the angle from 40 deg. to 0 deg. the received signal intensity increased from 3 to 4 times. These results have also been verified by tests made during the erection of the new Telefunken antennas.

The knowledge thus gained—that the optimum radiation of horizontal antennas is most advantageous when radiation is approximately parallel to the earth's surface—proved that we

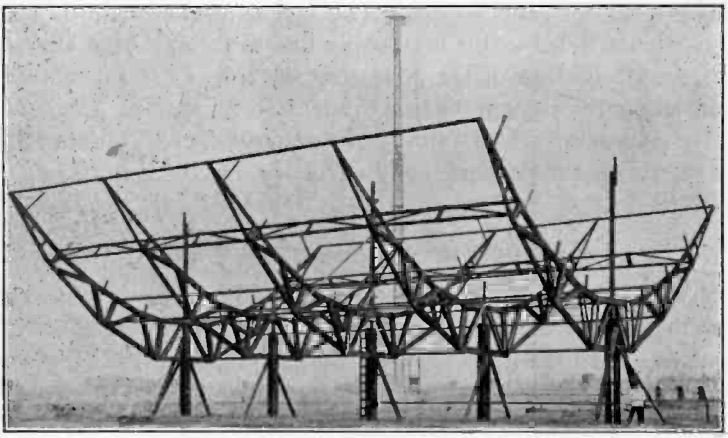

Fig. 3—Rotatable Reflector in the Setting for A Radiation Angle of 90 Degrees.

could dispense with the parabolic reflector, as horizontal radiation can be achieved more easily with plane antennas and reflectors. Tests with such antennas were made parallel to those described above. We shall report on these tests later on.

We also endeavored to determine the optimum angle of incidence of the horizontal component of the received wave by means of the above mentioned rotatable reflector, shown in Figs. 2 and 3, together with the fixed reflector system built alongside it for horizontal radiation. A modern short-wave receiver (two stages of r.f. and two stages of a.f. amplification with a separate heterodyning oscillator) was connected to the energy line of the antenna hanging in the parabola. The tests were carried out by Herr A. Gothe. During reception the reflector was

turned from 40 deg. to 120 deg. When turning it was found that reception remained unchanged in the region from 40 deg. to about 60 deg. From 60 deg. to 90 deg. and 120 deg., signal intensity continuously diminished. Reception with the fixed reflector set at 0 deg. was just noticeably better than the reflector at 40 deg. (The antenna of the fixed reflector hung at a height of 11 meters while that of the rotatable reflector hung at a height of 8 meters.) The ratio of signal intensity for the reception angles 0–40 deg.

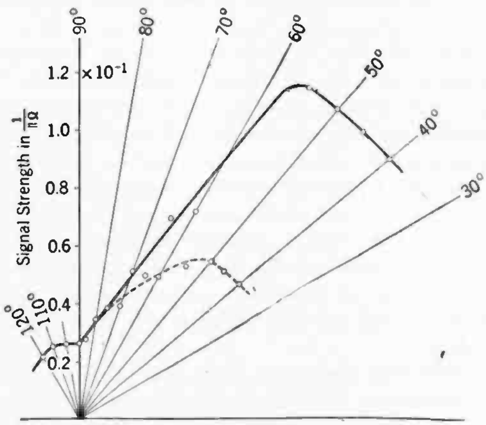

Fig. 4—Signal Strength in Reciprocal Parallel Ohms. Tests on Nov. 30 and Dec. 1, 1927.

to that for the angle 90 deg. is about 4 to 1. We can thus assume that the incoming horizontal radiation affects the antenna system at a small angle, i.e., we can use the same antenna arrangements for the reception of the horizontal component of the incoming wave that were found most suitable for the transmitter. Of course the above reception test is only of limited value. The tests could be made only during a few hours in the forenoon while the large transmitter in Nauen was idle since the rotatable reflector is set up on the grounds of the Nauen station.

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MAGNETOSTRICTION OSCILLATORS*

By
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(Rumford Professor of Physics, Harvard University, Cambridge, Mass.)

Summary—*The present paper describes a newly discovered method of using magnetostriction to produce and control electrical and mechanical frequencies of oscillations in a range of frequencies extending from a few hundred cycles per second to more than three hundred thousand cycles per second. The method involves the interaction of the mechanical vibrations of a magnetostrictive rod and the electric oscillations of an electric circuit in such a way that the electric currents in the circuit stimulate the rod to longitudinal vibration by magnetostriction and the vibrations of the rod react by magnetostriction on the electric circuit to maintain constancy of frequency.*

The constancy of frequency obtained compares favorably with that obtained with the piezo-electric crystal oscillators. For ease of construction and operation the magnetostriction oscillator has a great advantage over the piezo-electric oscillator, particularly in that the construction and adjustment of the magnetostriction vibrators is so simple that large numbers of standards of frequencies all operable with the same electrical circuits may be had at small expense.

The magnetostriction oscillators supply a particularly pressing need in the range of frequencies below twenty-five thousand cycles per second in which range crystal control is impractical on account of the expense of obtaining sufficiently large crystal vibrators. In the range between twenty-five thousand cycles per second and three hundred thousand cycles per second the magnetostriction oscillators and the crystal oscillators have a common field of usefulness. At frequencies greater than three hundred thousand cycles per second, the magnetostriction oscillators (although active up to two million cycles per second) are feeble with the present arrangement of apparatus. Their harmonics may, however, be employed up to frequencies of several millions per second.

This account contains also methods of calibration of the vibrators and their use in the calibration of wavemeters and frequency meters, data on the velocity of sound in various metallic alloys, data on the elastic constants of metals, including their temperature coefficients, description of methods of sound production, and a theoretical investigation of sound propagation in a viscous magnetostrictive medium.

Circuits and Mounting of Magnetostriction Oscillator for Controlling Oscillations in a Vacuum-Tube Circuit. As shown in Fig. 1, two coils are employed, one, L_1, in the plate circuit

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and the other, L_2, in the grid circuit of a high-μ vacuum tube. The magnetostriction rod, R, which we may call the vibrator, is placed axially within the coils, and rests centrally on a support between the coils, or if desired is held in a clamp at the support. In the diagram the right-hand coil is in the plate circuit in series with a B-battery. The left-hand coil is in the grid circuit. A variable air condenser C is connected between the plate and grid, so as to be across both coils. Sometimes the condenser C is connected across only one of the coils.

By means of plugs and sockets the double-coil unit may be replaced by others of different inductances. With a given coil

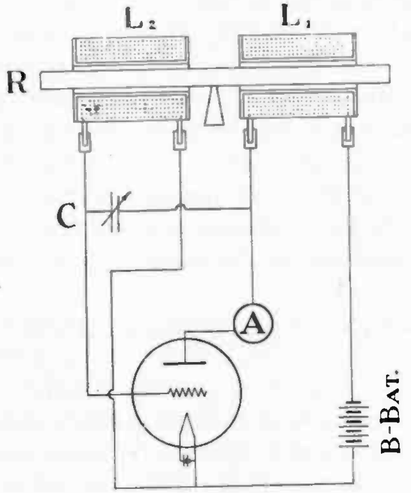

Fig. 1—Oscillator Circuit.

unit many different rods may be used by merely pulling out one and putting in another. The rod is free within the coils, which may have a clearance as large as the diameter of the rod itself. The rod is magnetized permanently by the plate current, or by a permanent magnet placed near it.

A direct-current milliammeter at A serves to indicate the plate current, and by its change with change of C to indicate the presence of oscillations.

Reversed Coil Note. One fact is to be noted that for the best operation of the apparatus as a constant-frequency device, the coils are so wound and oriented that a steady current flowing from the filament to the plate and a steady current, if there were

one, flowing from the filament to the grid produce magnetic fields in the same direction along the axis of the coils. This sense of the winding of the coils with respect to each other is opposite to that of the familiar electric oscillator circuits; but it should be noted that such an arrangement as that here shown, with certain values of circuit constants, will oscillate electrically without the rod or with the rod restrained.

Operation of the Magnetostrictive Rod in Rendering the System Oscillatory. A system such as is shown in Fig. 1 may be entirely non-oscillatory when the rod is restrained from vibration by being held or when the condenser C has a value far removed from the value required to give the circuit a period near the period of vibration of the rod. In such a case when the rod is released and the condenser has, or is made to have, the proper value, the rod and circuit fall into oscillation with a frequency which is essentially the frequency of the rod, and the frequency remains practically unchanged even when the condenser is varied over a large range or removed altogether. With proper choice of the coils the condenser is unnecessary.

Numerical data as to the constancy of frequency will be given below.

The existence of the oscillations is evidenced by the sound emitted by the vibrating rod, if its frequency is within the audible range; or, whether audible or not, the vibration is evidenced by the change of direct-current indication of the plate milliammeter. When the rod is allowed to vibrate the plate current changes to double or triple the value it has when the rod is restrained.

Operation of the Magnetostrictive Rod in Stabilizing the Frequency of an Electrically Oscillatory System. If we consider the circuit of Fig. 1, and especially if we note that the electrical feed-back between grid coil and plate coil is the reverse of that usually employed in producing electrical oscillations, we may understand that with a given choice of condenser, coil-winding, and coil-spacing, the system may or may not be electrically oscillatory when the magnetostrictive rod is restrained from vibration.

In the preceding paragraph note is made of the action with a non-oscillatory electrical system, which is the preferable mode of operation of the magnetostrictive system when employed with low-frequency vibrations of say five hundred to three thousand cycles per second.

At higher frequencies ranging from three thousand to three hundred thousand cycles per second, it is more convenient, and just as reliable, to allow the system to be electrically oscillatory even when the rod is restrained, and to employ the magneto-

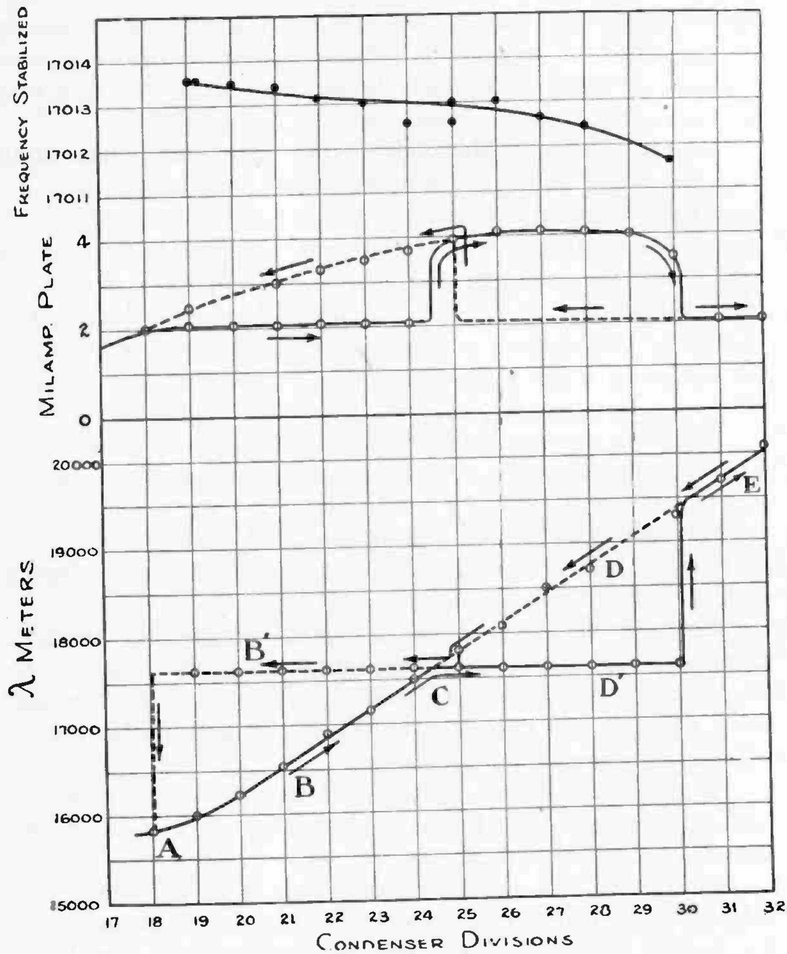

Fig. 2—Illustrating Stabilization of Frequency.

strictive rod merely to stabilize an already existing frequency of the electrical system when the latter is independently adjusted to a value near resonance with the period of mechanical vibration of the rod. This is done as follows: Any given rod, say one of frequency of twenty thousand, is placed in the coils. The

plate milliammeter is observed as the condenser C is varied. At a certain value of C, the plate current suddenly jumps to a large value (from one and one-half to three times its previous value). This indicates the incidence of rod-vibrations. The condenser may now be adjusted through a considerable range with no material change of the electrical or mechanical frequency of the system. It may be left oscillatory for days without changing frequency although the electrical characteristics may undergo large changes in that time.

General Note on Materials of the Magnetostrictive Rods. This research, which has now extended over some years, has concerned itself largely with the study of materials for the vibrators. The qualities required are large magnetostrictive effects and constancy of mechanical frequency in spite of changes of temperature and of intensity of magnetization, coupled with constancy of frequency in spite of changes of condenser settings, vacuum-tube characteristics, plate currents, and filament currents.

For these purposes pure iron and irons with various carbon contents are relatively useless, as having too small a magnetostrictive effect.

Pure nickel on the other hand is a good vibrator with, however, some lack of stabilizing power in that detuning slightly affects the frequency.

Alloys of nickel and iron in certain proportions are good vibrators, especially those having about 36 per cent nickel and 64 per cent iron (that is, of about the constitution of invar and Stoic metal). This alloy has, however, a large temperature coefficient of frequency.

Alloys of chromium, nickel, and iron are good vibrators, and for many purposes commerical Nichrome is one of the best materials easily available.

An alloy of nickel and copper known as Monel metal, containing 68 per cent Ni, 28 per cent Cu, and small percentages of Fe, Si, Mn, and C, is a very powerful oscillator. It usually has too small a residual magnetism to oscillate without an auxiliary polarizing means.

Alloys of cobalt and iron are strong vibrators.

Tubes of nickel make good oscillators for qualitative work and demonstration purposes and for sources of sound, but are somewhat lacking in constancy as frequency-stabilizers. Such

tubes of nickel wholly or partly filled with lead or type metal permit the easy construction of low-frequency vibrators because the velocity of sound in lead is small and gives a low-frequency of longitudinal vibration without excessive lengths of the rods.

By using a tube of material that has a negative temperature coefficient of frequency (such as nickel), in combination with a tight-fitting internal core of metal that has a positive temperature coefficient of frequency, (such as stoic metal), I have made composite vibrators of frequency practically independent of temperature. Other composite vibrators are described below.

All of the vibrators are made more powerful by annealing.

Mechanical Vibrations Longitudinal. In most of the applications of the magnetostrictive vibrator to the production and stabilization of frequency I have employed the longitudinal vibrations of the rod either in its fundamental mode or some harmonic mode of longitudinal vibration. In the designation of constants in this paper, unless otherwise stated, reference is to the fundamental mode of longitudinal vibration. It is usually not worth while to use harmonic modes of vibration of the rods since new rods of any desired frequency can be made and calibrated with such ease that the harmonic mechanical vibrations are interesting only in studies of the mechanics of the rod itself. Investigations of this character are now under way.

By sending a current lengthwise through the rod so as to give a circumferential magnetic field and at the same time applying a current to the solenoid, it is theoretically possible to produce torsional oscillations in the rod and these may be used to stabilize frequencies. I have found evidence of these torsional vibrations, but because of the complication of apparatus involved, these torsional oscillations are at present left out of the account.

Vibrators Magnetically Polarized. The rods are polarized by a steady state of magnetization upon which the oscillatory magnetizing forces are superposed, so that the resulting state is an increase of magnetization when the oscillatory current is in one direction and a decrease of magnetization when the oscillatory current is in the other direction. These two states are accompanied by an increase (or decrease) of length and a decrease (or increase) of length, respectively. If the rod were not thus polarized the change of length would be the same for each

half cycle of the current and would result in a mechanical vibration of double periodicity.

The polarization of the rods is usually attained by permanently magnetizing them in advance by a solenoid traversed by a strong direct current. With most substances the remanent magnetism is sufficiently strong to keep the rods sensitive as oscillators through years of normal use as standards of frequency in spite of any demagnetizing effects of the oscillations. The plate current of the tubes also assists in the polarization provided the rods, if permanently magnetized, are always inserted with their poles in the proper direction, as may be indicated on the coil mounting.

In cases of metals, like Monel metal, which have very small residual magnetism, I find that a small horse-shoe permanent magnetic placed in the vicinity of the rod is sufficient to give the required polarization, even when the small horse-shoe permanent magnet is 15 cm from the rod. With large oscillatory currents the polarization should be correspondingly large so that reversals of magnetization do not occur.

First Step in Explaining Action of Magnetostrictive Rod. Along with the description of the apparatus occasional paragraphs are introduced explanatory of the theory of operation, with a final mathematical treatment of the system. Magnetostriction is the distortion of a body (in this case the lengthening or shortening of the rod) when magnetized. A rod of nickel when magnetized shortens by about one one-millionth of its length for a magnetizing field of one gauss. This is the observed fact when the magnetization is produced by a steady magnetizing force. This shortening is thus very small, for the reason that the shortening must take place against the enormous elastic force of the body. On the other hand, when the specimen is magnetized by a force that increases and decreases in an oscillatory manner at a period resonant with the period of the body the shortening and lengthening may be more than one hundred times as great as that obtained with the same magnitude of constant current applied to the specimen. In the resonant oscillatory case the contraction and expansion are no longer opposed by the elastic force of the body but only by its viscosity. We may call the decrease or increase of length under magnetization the *direct effect*.

There is also an *inverse effect*. When a magnetized bar is stretched mechanically its state of magnetization is changed.

We may now apply these facts to the system of Fig. 1. Any small fortuitous change of current through the plate coil L_1 changes the magnetization of the rod and causes it to be deformed (lengthened or shortened). This deformation is propagated along the rod to its left-hand end and exists temporarily as a deformation within the coil L_2. The deformation changes the state of magnetization and consequently induces an electromotive force in L_2. This acts on the grid and produces an amplified current change in the plate circuit and in L_1. The oscillating currents in the system thus build up to a large amplitude with a frequency determined by the frequency of longitudinal mechanical vibration of the rod.

Sample Exhibit of Rods. Fig. 14 is from a photograph of several rod vibrators. *G* is a set of Stoic metal vibrators with a range of frequencies extending from ten thousand to thirty thousand cycles per second at intervals of one thousand cycles per second. These are described in Table I. *H* is a set of rods of Nichrome for each thousand cycles extending in range from twenty-six thousand to fifty-seven thousand cycles (see Table II). *F* is a rod of Nichrome with a frequency of 117,705 cycles per second. *D* shows a nickel tube filled with type metal. On account of the low velocity of sound in the type metal the specimen has a frequency of two thousand cycles per second, while a solid nickel rod or a nickel tube of the same length would have a frequency of nearly four thousand. *E* is a part of a similar tube, which is 94.35 cm long, and is filled with lead. It has a frequency of one thousand cycles per second, which can be adjusted over a range of some seven cycles by clamp weights that may be moved nearer together or farther apart to get a higher or lower frequency. By using these movable weights this rod or a harmonic of it can be brought to beat zero with other standards. *C* is a solid oscillator of stainless steel (about 11 per cent chromium). It has a frequency of 23,640 cycles per second, and is here shown to call attention to the fact that rods of large diameters do not fail to vibrate even at high frequencies. In fact the specimen *A* is a thin disc between corks in a glass tube and while 1.5 cm in diameter is only about 2 mm long and has a period of about a million and a half cycles per second. It is, however, a very feeble oscillator and evidences its oscillations only by transient clicks heard in a telephone in the plate circuit as the tuning condenser passes through resonance.

At *B* is shown a Nichrome oscillator of frequency 102,000 cycles per second in a sealed glass tube in vacuo, in which it is loose. In the picture, gravitation has pulled the oscillator to the lower end of the inclined glass tube. In operation the glass tube is placed axially in a horizontal position in the coils of the oscillator, and the rod is then centrally supported within the glass tube and within the coils. The mounting in a sealed glass tube has the advantage of permanence and avoids heating of the rod by the body temperature when it is handled. The absence of air or gas in the tube prevents the production of stationary sound waves in the tube, which might slightly affect the period of the rod, but this effect is very small.

TABLE I

LENGTH AND FREQUENCY OF STOIC METAL RODS AT 20 DEG.C. DIAMETER 0.79 CM.

Specimen No.	Frequency Cycles per sec.	Length Cm	Length in M × Frequency
10	10001	20.815	2081.7
11	11005	18.91	2081.0
12	11985	17.36	2080.6
13	12990	16.01	2079.7
14	14000	14.85	2079.4
15	14981	13.87	2077.8
16	16009	13.00	2081.2
17	17006	12.24	2081.5
18	18015	11.55	2080.7
19	19013	10.94	2080.0
20	20003	10.40	2080.3
21	21007	9.90	2079.7
22	22008	9.44	2077.5
23	22970	9.035	2075.2
24	24009	8.65	2076.8
25	24992	8.33	2081.8
26	25979	8.01	2080.9
27	26981	7.70	2077.5
28	27966	7.44	2080.5
29	29000	7.17	2079.2
30	29981	6.93	2077.7
		Average	2079.6 ± 2

$v_{\text{stoic}} = 2 \times \text{Length} \times \text{Frequency} = 4160 \pm 2$ meters per sec. at 20 deg. C.

A great variety of rod sizes are in use in various researches now under way at this laboratory.

Lengths and Frequencies of Rods. Table I contains data obtained with a set of Stoic metal rods. These are the rods shown at *G* in the photograph. The frequency values given in the second column are accurate to 1/100 of 1 per cent. The lengths are not accurately known because the ends of the rods

are not accurately true. The errors in the measurements of these lengths are of the order of 0.1 mm which amounts to more than 1/10 of 1 per cent for the shorter rods.

It is seen that the length of the rods times their frequencies gives a constant to the degree of precision to which the lengths are measured. This constant, when doubled, gives the velocity of sound in the metal, which is

$$v_{\text{stoic}} = 4160 \pm 2 \text{ m per sec. at 20 deg. C.}$$

All of these rods have roughly the same diameter, and the fact that there is no progressive change in the values of the last column indicates that there is no appreciable end-correction for the velocity determination.

The importance of this result for the present purpose is that a whole series of vibrators can be precomputed as to length with sufficient accuracy to make their final adjustment to required frequency very simple. A rod can be predetermined and cut in a lathe to 0.01 cm so that the final frequency adjustment to a standard value requires very little grinding. The end is ground off to raise the frequency. If too much is ground off at the end, it can be corrected by grinding away a little from the girth near the center of the rod.

Table II contains a similar set of observations of frequency for different lengths of Nichrome. Velocities for a large number of alloys are given below.

Experimental Data Illustrating the Manner in Which the Magnetostrictive Rod Functions in Controlling Frequency. Illustrative of the action of the rod as a frequency-controlling element the experimental curves of Fig. 2 are given. These are from observations taken with a rod (No. 17) of Nichrome in the coils and circuit of Fig. 1. In the lower part of Fig. 2 electric wavelengths λ, read on a precision wavemeter, are plotted against condenser divisions of the condenser C of Fig. 1. Readings were taken first with the rod restrained by holding it with the hand. A plot of λ versus C for the rod thus restrained is the curve $ABCDE$ of Fig. 2.

Next readings were taken with the rod free, starting with small values of the condenser C. These readings plotted give the curve $ABCD'E$, with a constant λ along the element D' of the path.

As a third operation, with the rod free the condenser was

started at large values of condenser and gave the curve $EDB'A$, with constant λ along the element B' of the path.

As a fourth operation it is noted that when we have once got the rod vibrating by either of the above operations we can pass back and forth along the whole of B' and D' (i.e. from 18 divisions to 30 divisions of the condenser) and the wavelength remains essentially constant.

TABLE II

LENGTH AND FREQUENCY OF NICHROME RODS AT 23 DEG.C. DIAMETER 0.96 CM.

Specimen No.	Frequency Cycles per sec.	Length Cm	Length in M × Frequency
26	25999	9.58	2490.7
27	27000	9.21	2484.0
28	28000	8.87	2486.4
29	29005	8.56	2482.8
30	29992	8.27	2480.3
31	31005	8.02	2486.6
32	32011	7.77	2487.2
33	33006	7.55	2491.9
34	34011	7.32	2489.6
35	35002	7.13	2495.6
36	36002	6.88	(2476.9)*
37	37004	6.73	2490.3
38	38004	6.55	2489.2
39	39005	6.38	2488.5
40	40004	6.23	2492.2
41	41007	6.06	2485.0
42	42000	5.93	2490.6
43	43005	5.79	2490.0
44	44009	5.66	2490.9
45	45008	5.53	2488.9
46	46004	5.42	2493.4
47	47009	5.30	2491.4
48	48011	5.20	2496.5
49	49008	5.09	2494.5
50	49996	4.99	2494.8
51	51040	4.87	2485.6
52	52000	4.78	2485.6
53	53062	4.69	2488.6
54	54027	4.61	2490.6
55	55014	4.53	2492.1
56	56042	4.45	2493.9
57	57015	4.37	2491.5
		Average	2490.3

$v_{\text{Nichrome}} = 4981$ m per sec. at 23 deg. C.

*Inconsistent on account of grinding at girth for adjustment.

The wavemeter measurements are not sensitive enough to detect any change of frequency along this path $B'D'$. To measure this quantity resort was had to beats between the oscillating system with rod No. 17 under investigation and a second oscillator with magnetostriction-rod control. Since the total change of

No. 17 was of the order of one cycle per second in seventeen thousand, the second oscillator, known as No. 117.7, was chosen to have a frequency about seven times that of No. 17, and beats were observed between the seventh harmonic of No. 17 and the fundamental of No. 117.7. This means that one cycle per second change in No. 17 gives seven cycles per second change in the beat note, which can be measured to about one cycle per second.

With this device the actual frequencies of the system stabilized by rod No. 17 against condenser settings are plotted as the top curve of Fig. 2. This curve shows that a change of the condenser from 19 to 30 divisions changes the frequency of the system by only 1.5 parts in seventeen thousand. This effect is discussed further in the next section.

In this experiment I have changed the condenser through a wide range of values, so as to make the change of frequency as much as possible, but when used as a constant frequency apparatus the condenser is brought always to the value which makes the plate current a maximum so that repeated settings of the apparatus may be made with a much higher degree of precision than the 1.5 cycles in seventeen thousand cycles per second.

Let us look next at the middle curves of this Fig. 2, which exhibits the plot of plate current against condenser settings, when the rod is free to vibrate. The arrows indicate the sense of a change given to the condenser of the oscillator circuit. When the condenser, on being increased, reaches 24.5 divisions the rod begins to vibrate and the plate direct current jumps from two to four milliamperes, and remains about the same for further increases of the condenser up to 30.1 divisions when the rod ceases to vibrate. Now a reduction of the condenser leaves the plate current two milliamperes till $C=25$ divisions is reached when the plate current jumps again to four milliamperes and then gradually decreases as the condenser is changed further down to eighteen divisions, when the rod is found to have again ceased to vibrate. In fact with this particular set of apparatus constants the system ceases also to vibrate electrically at C equal to or less than eighteen divisions. This accounts for the smooth fall of plate current to its constant two-milliampere value. With more clearance in the coil between the rod and the coil or with other electrical or mechanical constants we may get an abrupt change of plate current at the left-hand part of the curves as well as at the right-hand part. With less clearance, or by putting a separate

condenser about each of the coils of Fig. 1, the apparatus can be so constructed that all oscillations cease whenever the rod is restrained from vibrating.

The Apparent Reactance of the Coil Containing the Tuned Magnetostriction Rod a Function of the Frequency. A crude view of the above result is that in the range of frequency-stabilization the system oscillates as a condenser-inductance circuit

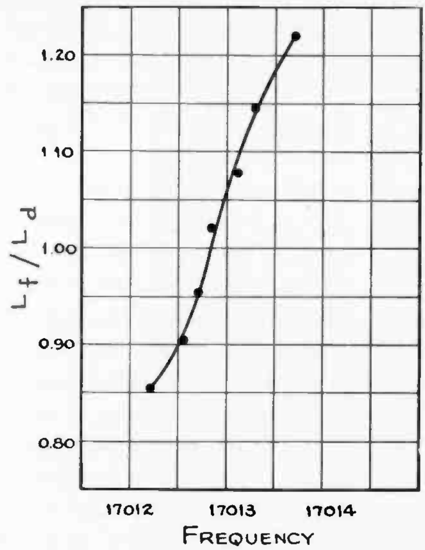

Fig. 3—L_f = Inductance Free; L_f = Inductance Damped; Plotted Against Frequency.

with an inductance that varies enormously with a small change of frequency. If we regard the wavelength-condenser curves of the lower part of Fig. 2 as having the equation

$$\lambda_d = 2\pi c\sqrt{L_d(C+C_o)} \text{ for the damped curve}$$

and

$$\lambda_f = 2\pi c\sqrt{L_f(C+C_o)} \text{ for the free curve}$$

we obtain

$$\left(\frac{\lambda_f}{\lambda_d}\right)^2 = \frac{L_f}{L_d}.$$

The values of this ratio are plotted against frequency in the curve of Fig. 3, from which it appears that the inductance of the

coil and free rod, in the range of its stabilization frequencies, changes by about 50 per cent for a frequency of 1.5 in 17013; that is, for a frequency change of less than 1/100 of 1 per cent.

Though the correct understanding of the device requires mathematical discussion, such as is given below, we may here regard the constancy of frequency, with large variation of condenser, as due to the fact that an increase of C makes the frequency lower. This is accompanied by a shift of L along the curve of Fig. 3 to a smaller value so that the product of $L\times C$, and consequently the frequency, is almost the same as before the increase of C and, in fact, with this particular magnetostrictive material (Nichrome) the frequency changes only 1/100 of 1 per cent for a change of 50 per cent in the value of C. The potency of the rod in controlling the frequency is seen by noting that if we omit the rod or restrain it from vibrating this change of 50 per cent in C causes 25 per cent change in frequency instead of the 1/100 of 1 per cent with the rod present and free.

Frequency Essentially Independent of Vacuum-Tube Voltages and Characteristics. I have made numerous experiments that show that the very large change of plate voltage from 135 volts to 67 volts changes the frequency of oscillation of the magnetostriction controlled system by only about one in thirty thousand. Voltage change of the filament battery from a condition of practically zero emission to the point of destruction of the filament or a change of the inductance of driving coils over the whole range of oscillatory operativeness or a change of the tubes to tubes of widely different characteristics affects the frequency within about the same limits.

These various notes as to constancy apply to annealed Nichrome rods. Some of the other materials and particularly certain tubular vibrators are not quite so constant in these particulars, but are still very serviceable when less precision is required.

Temperature Coefficient of the Nichrome Vibrators. The temperature coefficient of the frequency of the Nichrome vibrator is

$$\frac{\Delta f}{f\Delta\theta} = -0.000107/\text{deg. C.}$$

where f = frequency, Δf = increase of frequency for a change of temperature of $\Delta\theta$ degrees Centigrade. This equation means that the frequency decreases about 1/93 of 1 per cent per degree Centigrade.

The temperature coëfficient of other materials is given in a later section.

Comparison of Constancy with That of the Piezo-Electric Crystal Vibrators. For the purpose of comparison of the magnetostriction oscillators with the piezo-electric crystal method of frequency control to which I have contributed in previous researches I have made extreme tests on some of my best piezo-electric crystal frequency standards. One is a crystal, No. 28, mounted *in vacuo* in an accurately designed and carefully machined holder. When operated under constant conditions its absolute frequency has been repeatedly measured and shows variations below 1/500 of 1 per cent. However, care must be taken to keep the circuits constant with this crystal oscillator as the data of Table III show.

TABLE III
PIEZO-ELECTRIC CRYSTAL OSCILLATOR

Conditions		Frequency
Tube	Plate Volts	
199	45	28072
Daven 20	67	28064
Daven 20	112	28061
Daven 20	135	28058
201A	90	28056
201A	112	28054
201A	135	28052

It is seen that extreme variations of tubes and plate voltage changes the frequency of this crystal oscillator by 7/100 of 1 per cent.

This crystal also changes frequency to about the same extent with change of the inductance and distributed capacity of the plate coil. Table III compared with previous sections of this account shows that for equally violent change of the circuits, tubes, and voltages with the piezo-crystal oscillator and the magnetostriction oscillator the magnetostriction oscillator is much more constant as to frequency than is the piezo-crystal oscillator.

It should be noted, however, that in the matter of temperature coefficient of frequency the particular Nichrome magnetostriction oscillator with 1/93 of 1 per cent per degree Centigrade is more subject to temperature changes than the piezo-electric oscillators with 1/200 to 1/1000 of 1 per cent per degree Centigrade.

Below I give, however, descriptions of other magnetostrictive materials with temperature coefficients of about the same order as that of the piezo-electric crystal oscillators. The temperature effect in no case is permanent and the frequency comes back to its calibrated value when the temperature returns to normal for the calibration. A knowledge of the temperature permits the application of a correction to the rated calibration.

Magnetostriction Oscillator with Universal One-Stage Amplification. In order to increase the output power one or more stages of amplification may be employed. Fig. 4 shows a very simple and useful arrangement for a system to be operated at frequencies extending all over the audio- and radio-frequency

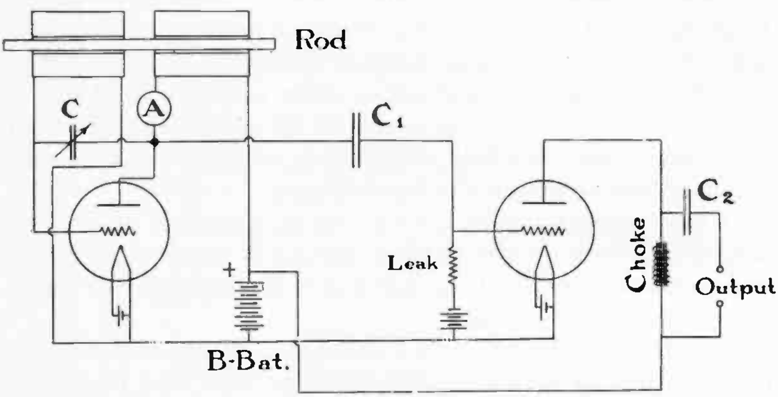

Fig. 4—Magnetostriction Oscillator with One-Stage Amplification. $C_1=0.1\ \mu f$; $C_2=2\ \mu f$; leak $=0.05$ megohms; A = milliammeters.

ranges. The oscillator tube shown at the left has the connections of Fig. 1. The grid of the amplifier tube at the right is connected through a condenser C_1 to the plate of the oscillator tube, and is provided with a leak resistance. The plate circuit of the amplifier tube contains a "speaker filter" unit consisting of an audio choke which is in series with the B-Battery and which communicates with the output terminals through a condenser C_2 of two microfarads.

The constants given in the legend to Fig. 4 are so chosen that the amplifier operates with considerable efficiency at both radio and audio frequency. In the latter case a loudspeaker connected to the output terminals gives volume enough to be heard throughout a large lecture room. This is the case also with radio oscilla-

tions upon which are superposed other radio oscillations to produce audio-frequency beats.

A commercial apparatus of this character made for me by the General Radio Company of Cambridge is shown in Fig. 15, and at the left in Fig 16. The coil units, containing rods, on top of the boxes are plugged into jacks and can be removed and interchanged. The upper cover of the box opens.

Twin Magnetostriction Oscillator. For calibration purposes we need two oscillators like that of Fig. 4, one of which is maintained constant by a standard magnetostriction rod, and the other of which is at a frequency to be compared with the rod. The two oscillators are then caused to interact and their beat frequency is determined or reduced to zero. After much experimenting I find that the best way to get the interaction is to connect their output terminals together through a small condenser and then to plug the telephone or other indicator in at one or the other of the output terminals. If the rod is left out of one of the coil units that half of the twin oscillator may be used as an ordinary variable electric oscillator.

I have found so much use for this arrangement that I have had both of these oscillators with common B-batteries and common A-battery terminals mounted in a single apparatus shown as the middle unit of Fig. 16.

The "speaker filters" of the two output circuits are connected with a switch so that if desired, either or both may be cut out and the B-battery and plate of the amplifiers be connected directly to the output terminals. This is useful in running a synchronous-motor clock, which requires a polarizing current, as the output apparatus. Such a clock made also by the General Radio Company from their own designs and kindly put at my disposal is shown in Fig. 15, and was used in timing some of the low-frequency rods (at about 1000).

Absolute Frequency Calibration by Magnetostriction Oscillators and the General Radio Synchronous-Motor Clock. Use is made of the adjustable magnetostriction rod of about 1000 cycles per second, which is shown in Fig. 15 mounted on top of the box containing the electric oscillator circuits and the one-stage universal amplifier. Used with the "speaker filter" cut out this drives the motor clock synchronously with the oscillations of the rod. The amplifier tube is a UX171, operating on 130 volts in the plate.

The synchronous clock has been provided with circuit-making contacts that close for a very short time each second of the clock.

For a standard of time with which to compare this motor clock Professor Stetson, of the Harvard Students'Astronomical Laboratory, has kindly permitted me to lead wires from his standard Riefler clock, which beats siderial seconds with an error not greater than two-tenths of a second per week. All relay contacting members are obviated in this circuit by the device of placing an inductance coil near the field coil of his relay, so that the local

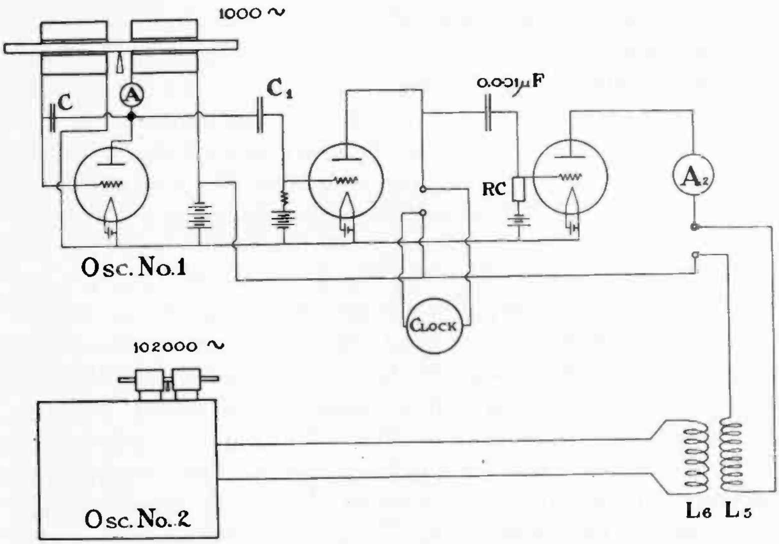

Fig. 5—Circuits for Absolute Calibration of Frequency.

current from the time wheel of the clock through his relay field acts inductively on my circuit and supplies second impulses without the inconstancy of any contact other than that of the time wheel of the clock. These second impulses arriving at this laboratory are amplified by a one-stage amplifier, to the output of which is connected a loudspeaker through the contacting points of the motor driven clock. When the standard Riefler clock and the motor clock make contacts at the same time the ticks are heard in the loudspeaker. By reading the motor clock for several successive coincidences accurate timing is obtained of the motor clock and of the magnetostriction driving rod.

For timing any other suitable magnetostriction rod, (say one of 102,000 vibrations per second) the latter is used to drive and control a second oscillator mounted on a second box like that of Fig. 15 or else the twin system is used with both the rods. The 1,000-cycle rod is now adjusted by moving the weights out or in along the rod to points where zero beat is obtained between the 102nd harmonic of the 1,000-cycle rod and the fundamental of the 102,000-cycle rod. When this adjustment is nearly perfect the remaining small adjustment is made by changing the tuning condenser of the 1,000-cycle system. In this way I have succeeded in reducing the beat frequency to one cycle in five seconds, which means an error of this adjustment of the harmonic of the low frequency to the fundamental of the high frequency of two parts in a million. Such accuracy is ordinarily not required, so that more tolerance is usually given to this adjustment.

It is interesting to note that the beats may be observed on a d. c. milliammeter as well as in a telephone. As a means of obtaining beats on the milliammeter the circuits of Fig. 5 are recommended.

In Fig. 5 Oscillator No. 2 has the circuits of Fig. 4 with a coil L_6 connected to its output terminals. Oscillator No. 1 has the same circuits for the two left-hand tubes with, however, the motor clock in place at the choke of the second tube. Paralleling the clock a radio-amplifying unit is employed for further amplifying the higher harmonics of Oscillator No. 1 and for suppressing its 1,000-cycle note and low pitch harmonics. The connection to the third tube is through a condenser of 0.001 μf, which has high impedance to these low notes. The customary grid leak of this third tube is replaced by a radio choke R C of about 0.1 henry, which has a small impedance for the low notes and a high impedance for the higher harmonics. The output circuit leads to L_5 inductively connected with L_6 so that the oscillations of the two systems are superposed in their output circuits, and their beats when nearly of zero frequency are observed on the d. c. milliammeter A_2.

In this way timing of the motor clock gives a direct standardization of the 102,000-cycle rod as well as of the 1,000-cycle. rod.

In a similar way any of the rods may be calibrated directly in one step. I have used harmonics of the 1,000-cycle rod up to its 234th.

To calibrate at the same time directly any higher frequency a double step is required.

Examples of Absolute Calibration of Some of the Rods. In calibrating Nichrome rod No. 30, the rod No. 1 (of about 1,000), was adjusted to give zero beats of its 30th harmonic with rod No. 30. Coincidences of the rod-clock seconds with the Riefler clock siderial seconds occurred as follows:

Coincidences Read on Rod Clock			Time Between Coincidences in Rod-Clock Seconds
hr.	min.	sec.	
3	14	31	396
3	21	17	395
3	27	42	399
3	34	21	

For computation we use

$$1 \text{ solar true second} = 1.00273 \text{ siderial seconds.}$$

$$1 \text{ rod second} = 1 + \frac{1}{397} = 1.00252 \text{ siderial seconds.}$$

$$\therefore \quad 1 \text{ solar second} = \frac{1.00273}{1.00252} = 1.00021 \text{ rod seconds.}$$

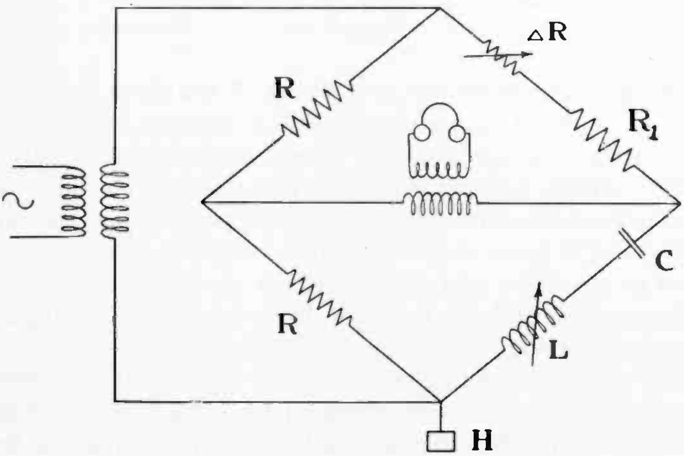

Fig. 6—Circuits of Audio-Frequency Meter.

The motor clock operated by the rod has its hands so geared to its motor that its time is correct when the motor is driven by a current of 1,000 cycles per second, so we have for the frequencies of the rods:

$$f_{\text{no. }1} = 1000.21,\ f_{\text{no. }30} = 30{,}006.3 \text{ at } 20.4 \text{ deg. C.}$$

Two other independent determinations of this rod No. 30 give 30,007.2 and 30,006.9 at 20.2 deg. C. The average of the three values is 30,006.8, with an average error of ½ cycle. Each of these calibrations had a timing period of about 20 minutes; by prolonging the time any required greater accuracy can be obtained.

The following values, Table IV, taken at random from my notebook have been obtained in the absolute calibration of a number of standards, and illustrate what can be done with even very careless work provided the standard second is good and is applied sharply to the apparatus.

TABLE IV
SAMPLE ABSOLUTE CALIBRATION OF STANDARD

Standard No.	Rod No. 30 at 20.3 deg. C.	Rod No. 102 at 20.6 deg. C.	Rod No. 117.7	Crystal No. 5884
Cycles per Second	30006.3 30006.9 30007.2	102078 102085 102084 102084 102083 102084	117718 at 21.9 deg. C. 117679 at 24.5 deg C 117705 at 23.0 deg C.	5884707 5884722
Average	30006.8	102083	117701 at 23 deg. C.	5884719

Referring to the values for rod No. 117.7 the three values were taken at different temperatures and if reduced to a common temperature of, say 23 deg., these values become 117704, 117689, 117705, averaging 117701 with an average error of 2 cycles per second. With this correction for temperature the values for No. 117.7 have about the same consistency as the other values in the table, and the variations in the table amounting to about 1/500 of 1 per cent are due to inaccuracy arising from the paucity of the coincidence observations.

The measurements of the frequency of Crystal No. 5884 of about 5884 kilocycles were obtained by using the rod of 1000 cycles adjusted to 997.28 cycles so that its 118th harmonic beats zero with rod No. 117.7 and at the same time beats were measured between the 50th harmonic of No. 117.7 and the fundamental of Crystal No. 5884. The latter number of beats per second was found to be 772, so we have $f_{5884} = 50(118 \times 997.28) + 772 = 5{,}884{,}722$. This double operation steps up the 1000-cycle frequency to its 5900th harmonic.

It is interesting to note that this crystal No. 5884 can also be used at all of its harmonics up to its 30th harmonic to measure frequencies up to 150 million cycles.

Mr. M. T. Dow, Dr. Frederick Drake, and I are using such a calibration in the precision measurement of the velocity of electric wave.

By the methods here described the several rods of Fig. 14 have been calibrated and intercompared. In the intercomparison the differences between fundamentals or harmonics of various oscillators may be conveniently measured by a bridge-type of audio-frequency meter such as is described in the next section.

Audio-Frequency Meter. I here call attention to a bridge-type of audio-frequency meter involving well known circuits[1] that I have found useful for measuring audio frequencies. A photographic view of this apparatus is shown as the right-hand unit of Fig. 16. The circuits are shown in Fig. 6 and comprise a bridge of three resistance arms and one arm of a variable L in series with fixed C. The two resistances R R are equal. The resistance R_1 plus ΔR is equal to the resistance of the branch $L\,C$ which is chiefly the resistance of L. Since L is of copper wire it has a temperature coefficient. This is compensated by the small adjustable resistance ΔR, which when necessary is independently adjusted when the bridge is to be balanced. The chief variable element is L. At any given frequency, f, within the range of the apparatus the balance is obtained when

$$2\pi f = \frac{1}{\sqrt{LC}}\cdot$$

Frequencies are read on a direct-reading scale calibrated in frequency attached to the dial of L. One important point is that for repeatable readings with an accuracy of 1 part in 1000 the variable effects of body-capacity must be eliminated. I have found it advisable to provide the inductance L with a metal knob so that when one takes hold of this knob to adjust L he connects his body to the point H in Fig. 6.

The inductance L at full scale is about 200 millihenries. The capacity C is a three-step mica condenser, having the three values 0.04, 0.2, and 1.0 μf, which gives the instrument a three-

[1] Although this instrument has been in use here for many years it was apparently previously described and used as a frequency meter by Heydweiller and Hagemeister: *Verh. d. D. Phys. Ges.* **18**, 52, 1916. For other references see Banneitz: *Taschenbuch der drahtlosen Tel. und Tel.*

fold scale extending from 365 to 5000 cycles per second. The switch in the center of the photographic view of the instrument is for switching to different values of the condenser, and automatically switches the pointer to the proper direct-reading scale. The scale was drawn by hand on a bakelite disc from experimentally determined frequency readings and was then engraved on the disc.

In the instrument are included an input transformer, for connecting directly into the input circuit of a vacuum-tube oscillator, and an output transformer connecting to head telephones or a loudspeaker.

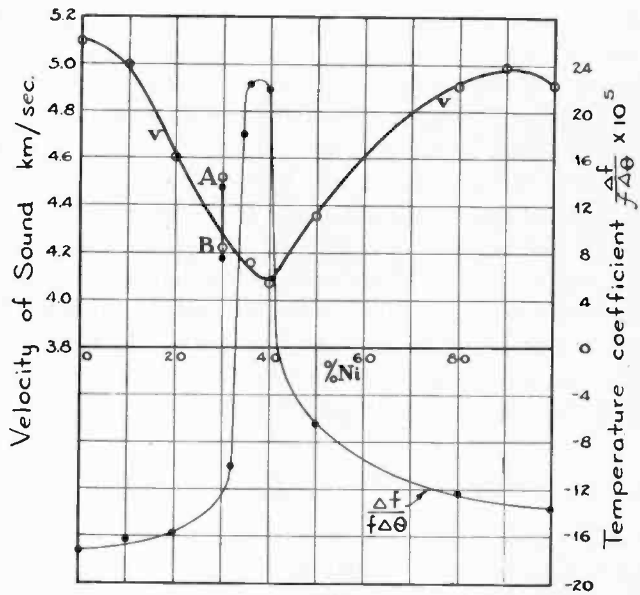

Fig. 7—Velocity and Temperature Coefficient of Frequency of Nickel-Iron Alloys of Various Percentages of Nickel.

Absolute Calibration of Audio-Frequency Meter of Fig. 6 by Nichrome Rod No. 30 with $f = 30{,}000$. An electric oscillator with frequencies variable to cover the range of the audiometer is made to beat aginst various harmonics of the fixed 30,000-cycle frequency of the rod No. 30. Practically, in the present calibration, this was done by using the Twin Oscillator of Fig. 16 (shown at the center) with the magnetostriction rod in its coil assembly plugged into one set of jacks on the instrument and with various coil-

pairs without magnetostriction core plugged into the other set of jacks. One pair of the output terminals of the Twin Oscillator were now connected to the input posts of the audio-frequency meter to be calibrated. A telephone receiver was at the output posts of the audio-frequency meter.

The procedure is as follows: Adjust the variable electric oscillator to beat zero with some harmonic of the magnetostriction rod, then adjust the audio-frequency meter for silence in the telephone and read the scale of the audio-frequency meter. Proceed *ad lib.* with other harmonics.

Table V gives the results. The value of the harmonic used is given in the column marked n. For example $n = 3/50$ means a beat zero between the 50th harmonic of the 30,000 cycles rod and the 3rd harmonic of the electric oscillator, to which the audiometer was set, giving $f = 1800$ cycles per second. This is tabulated in the second column.

The observations in this Table V were made hurriedly without any repetition of readings. Only the more striking harmonics (simple ratios) were used, and a large number of other values were passed over without being read, as there was no need of obtaining any more dense distribution of the calibration points. The accuracy of reading the scale of the instrument was only about 1 part in 1000 in the more open parts of the scale. Checks on the identity of the harmonics can be obtained by using other magnetostriction rods.

Absolute Calibration of a Wavemeter by Nichrome Rod No. 30. To show a further use of the magnetostriction standards this same rod of 30,000 cycles per second ($\lambda = 10{,}000$ meters) was used to obtain the values of Table VI in calibration of a wavemeter ranging from 233 to 2224 meters. The procedure was the same as in the preceding section, except that the electric oscillator coils were of small inductance so as to give high frequency. The telephone connected directly at the output of the Twin Oscillator served to evidence audible beats, which were adjusted to a zero-beat-frequency.

The wavemeter was placed near the electric oscillator coil and had its coil shortcircuited, while setting the oscillator to beat zero. Then the shorting switch of the wavemeter was opened and the condenser of the wavemeter was adjusted. As resonance was approached beats were again heard in the telephone. Changing the condenser of the wavemeter in one direction, we hear

these beats rise in frequency, then drop to zero, then appear again at a high frequency and gradually change to zero. The drop of the beats to zero at the setting between the two high-frequency beat values is the adjustment of the wavementer to resonance.

In Table VI n indicates the harmonics employed. This is here tabulated as $1/n$, since we are concerned with wavelengths. The wavelength λ of the wavemeter is obtained by taking $1/n$ times the electric wavelength (10,000) of the 30,000-cycle rod.

TABLE V

CALIBRATION OF AUDIO-FREQUENCY METER VS. NICHROME ROD NO. 30.

Scale of Instrument	f by No. 30	n	Scale of Instrument	f by No. 30	n
872	870	2/69	1760	1767	1/17
897	896	2/67	1800	1800	3/50
909	909	1/33	1818	1818	2/33
922	923	2/65	1871	1875	1/16
937	938	1/32	1909	1915	3/47
952	952	2/63	1935	1935	2/31
956	957	3/94	2000	2000	1/15
968	968	1/31	2068	2069	2/29
978	978	3/92	2140	2143	1/14
982	984	2/61	2223	2222	2/27
1090	1091	2/55	2305	2308	1/13
1130	1132	2/52	2395	2400	2/25
1181	1176	2/51	2500	2500	1/12
1228	1224	2/49	2605	2609	2/23
1252	1250	1/24	2722	2727	1/11
1278	1277	2/47	2999	3000	1/10
1330	1333	2/45	3165	3158	2/19
1390	1395	2/43	3330	3333	1/9
1462	1463	2/41	3535	3529	2/17
1498	1500	1/20	3740	3750	1/8
1543	1538	2/39	4000	4000	2/15
1581	1579	1/19	4285	4285	1/7
1603	1607	1/23	4478	4500	3/20
1620	1622	2/37	4595	4615	2/13
1660	1666	1/18	4710	4737	3/19
1692	1696	3/53	5010	5000	1/6
1710	1714	2/35			

In this section and the preceding section it is seen that the 30,000-cycle rod is used in frequency calibrations extending from 870 cycles to 1,200,000 cycles. The possible range is vastly greater than this.

In practice I no longer use directly the wavemeter or the audio-frequency meter for accurately measuring wavelengths or frequencies, but instead beat everything against the rods or piezo-crystals, and use the audio-frequency meter for measuring

differences of frequencies, and the wavemeter for identifying harmonics.

Study of Frequency, Sound Velocity, and Temperature Coefficients of Frequency of Various Alloys. I have investigated a large number of alloys for their magnetostrictive properties, and,

TABLE VI

CALIBRATION OF WAVEMETER LC_1 VS. NICHROME ROD NO. 30. READINGS ARE IN METERS WAVELENGTHS

Scale of Instrument	λ by No. 30	1/n	Scale of Instrument	λ by No. 30	1/n
2224	2222	2/9	866	869	2/23
2175	2174	5/23	832	825	1/12
2144	2143	3/4	799	800	2/25
2106	2105	4/19	768	769	1/13
2085	2084	5/24	712	714	1/14
2070	2068	6/29	662	666	1/15
2000	2000	1/5	621	625	1/16
1940	1944	7/36	574	578	1/17
1924	1923	5/26	553	555	1/18
1892	1892	7/37	523	526	1/19
1870	1875	3/16	514	513	2/39
1848	1852	5/27	502	500	1/20
1815	1818	2/11	475	476	1/21
1790	1786	5/28	454	455	1/22
1712	1714	6/35	435	435	1/23
1668	1667	1/6	416	417	1/24
1573	1579	3/19	401	400	1/25
1535	1538	2/13	383	385	1/26
1510	1515	5/33	368	370	1/27
1500	1500	3/20	356	357	1/28
1480	1481	4/27	344	345	1/29
1462	1463	6/41	333	333	1/30
1426	1429	1/7	322	323	1/31
1388	1389	5/36	312	313	1/32
1378	1379	4/29	303	303	1/33
1362	1364	3/22	295	294	1/34
1350	1352	5/37	285	286	1/35
1332	1333	2/15	276	278	1/36
1303	1304	3/23	270	270	1/37
1251	1250	1/8	263	263	1/38
1201	1200	3/25	257	256	1/39
1178	1176	2/17	251	250	1/40
1111	1111	1/9	245	243	1/41
1050	1052	2/19	238	238	1/42
999	1000	1/10	233	233	1/43
952	952	2/21			

by measuring the frequency of oscillation of a known length of specimen, have determined the velocity of a longitudinal sound wave in these various materials. These are recorded in column 2, Table VII. By making these measurements at various temperatures I have obtained the temperature coefficient of fre-

quency (column 3). By the formula

$$v=\sqrt{\frac{\text{Young's modulus}}{\text{Density}}}$$

I have computed Young's modulus (column 5) from measured values of velocity and density (column 4). This method gives high precision, and is interesting in that the value of the modulus is obtained for very small applied forces. Additional data of Table VII are described below.

TABLE VII

EXPERIMENTAL RESULTS FOR ALLOYS

Material	v m/sec	g $\times 10^6$	ρ g/cc	$E\times10^{11}$ Dyne / sq. cm.	a $\times 10^6$	h $\times 10^6$	b $\times 10^6$
Iron	5074	−171	7.688	19.79	12	−159	−354
Nickel	4937	−132	8.803	21.46	12	−120	−276
Stoic	4161	+224	8.02	13.89	1.5	+226	+446
Nichrome	4981	−107	8.269	20.52	12	− 97	−226
Monel	4549	−151	8.854	18.32	14	−137	−316
Stainless Steel	5430	−136	7.720	22.76	10	−135	−282
Stainless Iron	5133	−130	7.743	20.40	10	−130	−270
Nickel-Iron % Ni							
0	5074	−171	7.688	19.79	13.3	−158	−355
10	4919	−164	7.812	18.90	9	−155	−337
20	4582	−159	7.818	16.41	8	−151	−326
30	4527	+135			9	+144	+261
30	4241*	+ 77*	7.950*	14.29*	4*	+ 81*	+150*
32	4540	−101			3	− 98	−205
34		+182			2	+184	+362
36	4161	+224	8.020	13.89	1.5	+226	+446
40	4075	+218	8.042	13.36	5	+223	+431
50	4352	− 64	7.901	14.96	10	− 54	−138
60	non oscillatory						
70	non oscillatory						
80	4908	−124	8.521	20.52	12	−112	−260
90	4990		8.666				
100	4937	−132	8.803	21.46	12	−120	−276
Chrom-Iron % Cr.							
10	5290	−153	7.619	21.32	10	−143	−316
20	5448	− 90	8.028	23.82	10	− 80	−190
30	5392	−102	7.659	22.27	10	− 92	−214
40	4329	− 91	7.514	21.33	10	− 81	−192
Si Cr Fe%							
5 5 90	5166	−118	7.559	20.17			
5 10 85	5285	−111	7.581	21.17			
5 15 80	5192	−112	7.482	20.17			
5 20 75	4806	−144	7.488	17.30			
5 25 70	5473	−140	7.405	22.18			
5 30 65	5387	−133	7.414	21.52			
5.16 4.53 90		− 82					
Carbon-Steel % C							
0.8	5233	−110	7.849	21.49	11	− 90	−231
1.0	5209	−137	7.827	21.24	11	−126	−285
1.5	5217	−123	7.866	21.41	11	−112	−257

v = velocity of sound, g = temperature coefficient of frequency, ρ = density, E = Young's Modulus, a = coefficient of expansion, h = temperature coefficient of velocity, b = temperature coefficient of elasticity.

* After dipping in liquid air.

Other alloys are under investigation and will be reported in a later publication. Many of the specimens of the table contain a small quantity of manganese (about 0.3 per cent) added to make the specimen malleable.

Curves Showing Results for Velocity and Temperature Coefficients of Frequency with Alloys of Various Compositions. Fig. 7 shows velocity of sound in km per second and also temperature coefficient of frequency of vibration with rods of nickel-steel plotted against percentages of nickel of the rods. It is seen that the velocity has a minimum and the temperature coefficient has a maxi-

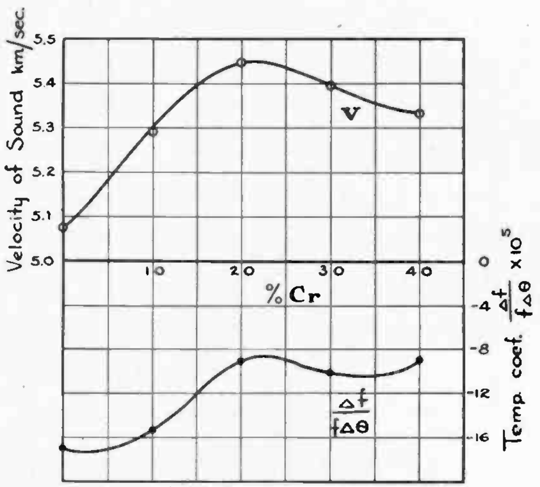

Fig. 8—Velocity and Temperature Coefficient of Frequency of Chromium-Iron Alloys with Various Percentages of Chromium (Abscissas).

mum at 36 per cent to 40 per cent nickel. This is at about the composition of Invar (36 per cent nickel). Fig. 8 contains corresponding curves for chromium-steel of various percentages of chromium; Fig. 9, similar results for various percentages of chromium in chromium-steels which contain also 5 per cent silicon. In Fig. 8 the velocity is a maximum and the temperature coefficient of frequency is a maximum at 20 per cent to 25 per cent chromium. These results, Fig. 7 and Fig. 8, suggest as a possible law *that in a binary metallic alloy the temperature coefficient of frequency is a maximum or minimum at the composition at which the velocity is a maximum or minimum, or the reverse.* Having found a means of extending the methods of the present research to non-magnetic

alloys also I have assigned to a research student the problem of testing this apparent law for a wide variety of alloys.

The curves of Fig. 9 show the effects of adding a third component, 5 per cent silicon, to the chromium-iron series. This added silicon introduces a large minimum of velocity at 20 per cent chromium, 5 per cent silicon, and 75 per cent iron. Indications of corresponding maxima or minima of the temperature coefficient of frequencies at compositions giving a maxima or minima of velocity are also apparent in these curves, but the

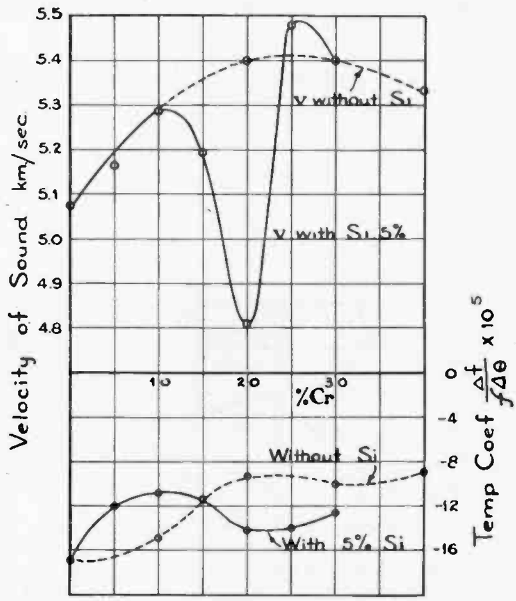

Fig. 9—Effect of Addition of 5 per cent Silicon to Chromium-Iron Alloys of Various Percentages of Chromium (Abscissas) and Rest Iron.

compositions employed were not selected closely enough together to make the result certain.

An interesting result is the largeness of the change of velocity with change of composition.

The points marked *A* and *B* of Fig. 7 were obtained with a nickel-steel of 30 per cent nickel. The values at *A* were obtained with the annealed specimen, and the interesting fact was noted that when the specimen was heated to about 50 deg. C it became non-magnetic and ceased to oscillate. When it was cooled down to 20 deg. C it again became magnetic and oscillatory, but re-

versibly lost or gained its magnetism as the 50 deg. C point was passed. This fact for about this composition has been previously observed by Hopkinson.[2] Acting on the facts there given regarding effects of cooling, I had my specimen dipped into liquid air. After coming back to room temperature it gave the points marked B in Fig. 7. It had become a new substance and no longer lost its magnetism with change of temperature over the range up to 100 deg. C.

Temperature Coefficients of Elasticity and of Velocity. Simple relations exist among various temperature coefficients, so that other coefficients may be obtained from the experimental data of Table VII combined with known quantities taken from the work of previous investigators.

Given $\Delta\Theta$ = increment of temperature,

$$a=\frac{\Delta l}{l\Delta\theta}=\text{coefficient of linear expansion,}$$

$$b=\frac{\Delta E}{E\Delta\theta}=\text{coefficient of Young's modulus } E,$$

$$g=\frac{\Delta f}{f\Delta\theta}=\text{coefficient of frequency of longitudinal vibration,}$$

$$h=\frac{\Delta v}{v\Delta\theta}=\text{coefficient of velocity of longitudinal wave,}$$

and

$$2lf=v=\sqrt{\frac{E}{\rho}}=\sqrt{\frac{EV}{W}}\cdot \tag{1}$$

In this equation (1)

l = length of a specimen, which has
f = frequency,
ρ = density,
E = Young's modulus,
W = weight,
V = volume.

If the specimen satisfying equation (1) is raised 1 deg. C in temperature W does not change and we obtain

$$2lf(1+a)(1+g)=v(1+h)=\sqrt{\frac{EV}{W}(1+b)(1+3a)}$$

[2] See Ewing: "Magnetic Induction in Iron and Other Metals," Van Nostrand, 1900.

Dividing this by (1) and performing the indicated operations for small values of the coefficients we obtain

$$1+a+g=1+h=1+\frac{b}{2}+\frac{3a}{2}$$

$$\therefore \qquad h=a+g, \text{ and } b=2g-a. \qquad (2)$$

Equation (2) enables us to compute the temperature coefficient of elasticity b and the temperature coefficient of velocity h from

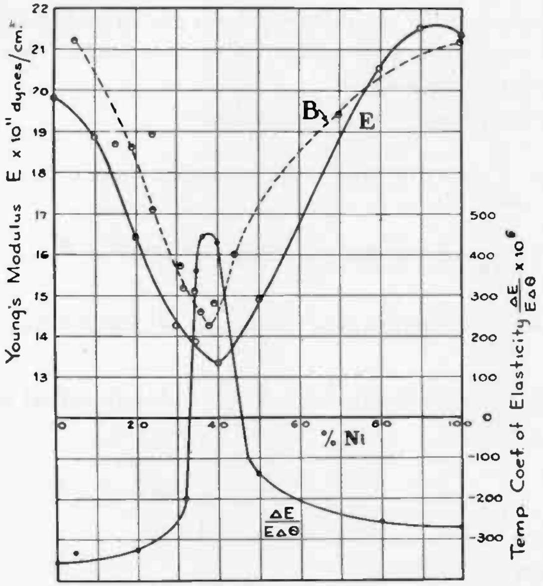

Fig. 10—Young's Modulus and Temperature Coefficient of Elasticity of Nickel-Iron Alloys with Various Percentages of Nickel (Abscissas).

the measured values of the temperature coefficient of frequency g and values of temperature coefficient of expansion a. Since the latter are small in comparison with g they are given sufficiently accurately in ordinary tables of constants.

Values of a taken from Bureau of Standards Circular No. 58 and from International Critical Tables are entered as column 6 of Table VII, and computed values of h and b are entered in columns 7 and 8.

Fig. 10 is a plot of E from my data on sound and also a plot of the corresponding values (Curve B) from the Bureau of

Standards Circular No. 58. The large differences between these curves may be due to the fact that the values given in the Bureau Circular are obtained at large stresses while my values are for the very small stresses of sound waves. On the other hand, small differences in composition, as the 0.3 per cent manganese in my specimens, or different heat treatment, may account for the differences. It should be further noted that my specimens were magnetized.

Methods of Obtaining Magnetostriction Vibrators of Zero or Very Small Temperature Coefficients of Frequency. In Table VII the temperature coefficients of frequency g of magnetostric-

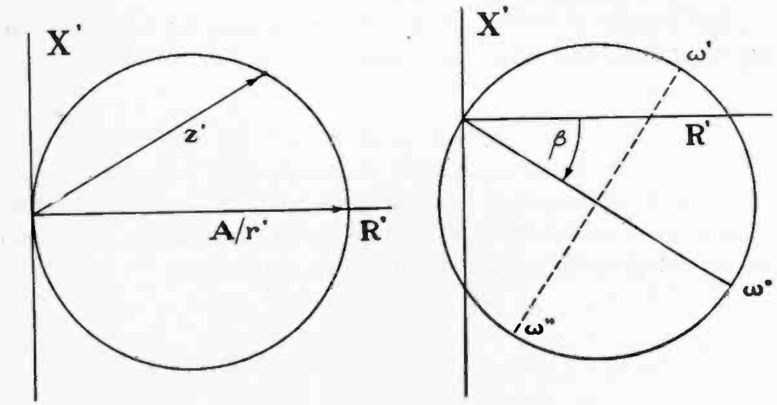

Fig. 11—Impedance Circle Diagrams.

tion vibrators of various alloys are given in column 3. In particular it is seen that the nickel-iron alloys vary from

$$g = -171 \times 10^{-6} \text{ to } g = +224 \times 10^{-6}$$

and that this coefficient is zero for alloys of 33 per cent Ni and 47 per cent Ni. Unfortunately these alloys are difficultt o produce with exact properties because the curve of temperature coefficient is very steep at these points. Furthermore, these materials are only very weak magnetostriction oscillators. With sufficient care in their production and heat treatment they may prove highly serviceable as oscillators of zero temperature coefficients. A further study of alloys of this class is under way.

In combinations of three metals I have found that a vanishing temperature coefficient is usually associated with non-magnetism or non-magnetostriction.

Consequently I have investigated the alternative method of composite vibrators made of different metals so arranged that the positive coefficient of one specimen counteracts the negative coefficient of another specimen, which have the merit of simplicity of construction and can be made of materials giving a strong resultant vibration.

Two kinds of composite vibrators have been employed with success:

(*a*) A central rod of negative coefficient with a rod of positive coefficient soldered end to end at each end of the central rod. This I shall call *longitudinally composite.*

(*b*) A tube of coefficient of one sign containing a tight-fitting core rod of coefficient of the opposite sign. This I call *concentrically composite.*

A number of vibrators of both these types have been made. For standards the concentrically composite type have more power in controlling frequency and are preferred. Two such vibrators consisting of nickel tubes with stoic metal cores driven into them at a tight press-fit were found to have coefficients

$$\frac{\Delta f}{f\Delta\theta} = -\frac{1}{50000} \text{ and } -\frac{1}{65000}$$

respectively. Smaller values of this coefficient can be obtained by better choice of relative diameters of the components.

It should be noted that the cause of the change of any of these vibrators with change of temperature is the temperature coefficient of elasticity of the materials and not the change of length or change of density, both of which are relatively small.

Elementary Theory of Dynamic Magnetostriction. As a simplification of the more exact treatment of the subject, such as is given in Appendix I, there is here presented a discussion based on the assumption that the rod acts mechanically as a pair of masses separated by an elastic member and damped by friction proportional to velocity, so as to satisfy the equation

$$f' = m\ddot{x} + r\dot{x} + \epsilon Sx/l. \tag{1}$$

In this equation the dots indicate time derivatives, and r, m, and ϵ are equivalent values of frictional resistance, mass, and Young's modulus respectively,

S = Area of cross section

l = half length of the rod

x = increase of length of the half rod-length due to the force f'.

The force f' is a periodic magnetostrictive force due to a periodic magnetic induction B of comparatively small amplitude superposed on a fixed induction B_o, which is used to polarize the specimen.

Law I of Magnetostriction.—As a first law of magnetostriction we shall assume that the magnetostrictive force f' caused by the periodic induction B is proportional to B and to the area of cross section S; that is,

$$f' = aBS, \tag{2}$$

where a (positive for some substances and negative for others) is a coefficient depending on B_o but otherwise assumed constant.

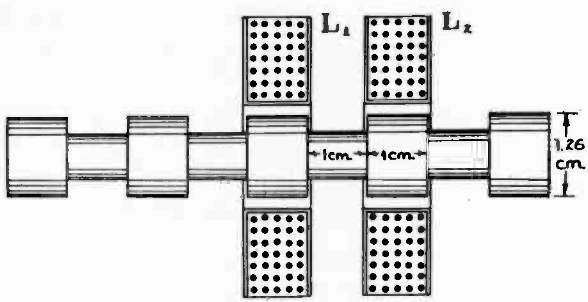

Fig. 12—Beaded Rods.

We shall regard B as made up of two parts B_i and B'

$$B = B_i + B', \tag{3}$$

where B_i = induction due to the periodic current i,

B' = induction due to the reverse magnetostriction effect (Law II).

Law II of Magnetostriction.—When the rod is stretched an amount $2x$ with an original rod-length $2l$ there is produced an induction B' proportional to x/l; that is,

$$B' = a'x/l. \tag{4}$$

Solution for Time-Derivative of x.—The substitution of (2), (3), and (4) into (1) gives

$$aSB_i = m\ddot{x} + r\dot{x} + \{\epsilon - aa'\} x/l, \tag{5}$$

of which the solution for the time-derivative of x on the assumption that B_i involves the time only in a factor of the form $e^{j\omega t}$ is

$$\dot{x} = \frac{aSB_i}{r + j\{m\omega - \epsilon' S/l\omega\}} \tag{6}$$

where as an abbreviation

$$\epsilon' = \epsilon - aa'. \tag{7}$$

Electrical Equations.—We shall next write the electrical equations. The alternating current i is related to the impressed emf e by the equation

$$e = Ri + \frac{d}{dt}\{\text{Flux linkage of } (B_i + B')\}. \tag{8}$$

The first two terms of the right-hand side of this equation give the electromotive force if the rod were damped so that it did not move. The remaining term gives the electromotive force due to the motion, which we shall call *motional* emf and shall designate by e', so

$$e' = \frac{d\phi}{dt}, \text{ where} \tag{9}$$

$$e' = \text{damped emf},$$

$$\phi = \text{Flux linkage of } B'.$$

If now we write

$$\phi = a''B' \text{ and} \tag{10}$$

$$B_i = L'i, \tag{11}$$

where a'' and L' are constants depending on the size, shape, and number of turns of the coil and on the permeability of the specimen, and combine (4), (6), (9), (10), and (11), we obtain

$$e' = z'i, \text{ where} \tag{12}$$

$$z' = \frac{aa'a''L'S/l}{r + j\{m\omega - \epsilon' S/l\omega\}}. \tag{13}$$

In equation (13) z' is the complex motional impedance of the system. ω is the angular velocity of the current. a, a', a'', and L' are coefficients defined by (2), (4), (10), and (11), respectively.[3]

[3] This theory and the discussion of the next section is essentially of the same character as that given by Professor Kennelly and the author for the impedance of telephone receivers. *Proc.* Amer. Acad. **48**, No. 6, 1912, and *Electrical World*, September, 1912.

Impedance Circle Diagrams. If we let

$$R' = \text{motional resistance}$$

$$X' = \text{motional reactance}$$

of the rod-coil unit, and as further abbreviations, write

$$A = aa'a''L'S/l \text{ and} \tag{14}$$

$$Z_m^2 = r^2 + \{m\omega - \epsilon' S/l\omega\}^2, \tag{15}$$

we find that (13) after rationalization gives

$$R' = \frac{Ar}{Z_m^2} \tag{16}$$

$$X' = \frac{-A\{m\omega - \epsilon' S/l\omega\}}{Z_m^2} \tag{17}$$

whence

$$R'^2 + X'^2 = A^2/Z_m^2.$$

The substitution of (16) so as to eliminate Z_m gives

$$R'^2 + X'^2 = AR'/r. \tag{18}$$

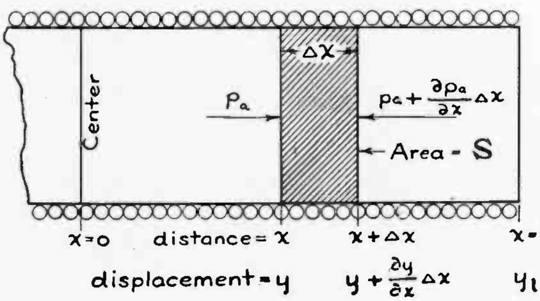

Fig. 13

This is the equation to a circle, passing through $R' = 0$ and $X' = 0$, and having a diameter A/r, and is represented as the left-hand circle of Fig. 11. Each value of ω gives a point of the circle. The circle is thus the locus of X' plotted against R', or, otherwise stated, it is a vectorial plot of z' as ω varies.

Impedance Circle-Diagrams With Diameter Dipping. In the preceding section the diameter of the impedance circle lies along the axis of motional resistance. Experimentally this is

found to be not the fact. The diameter of the circle usually dips by an angle which we shall call β.

This result can be obtained theoretically if we let one or more of the quantities a, a', a'', L' be a complex quantity independent of ω so that

$$Ae^{-i\beta}=aa'a''L'S/l. \tag{19}$$

This is equivalent to multiplying every vector z' by $e^{-i\beta}$ which gives the whole diagram the form of the right-hand circle of Fig. 11.

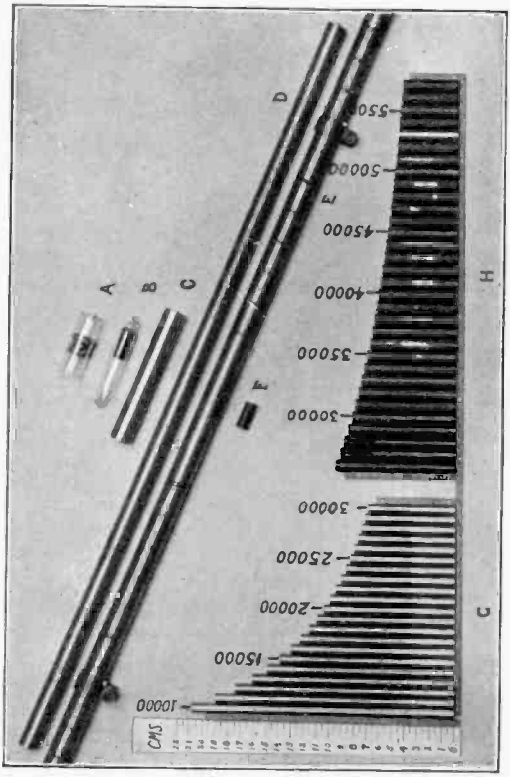

Fig. 14

As to the physical significance of complex values of a, a', a'', or L', which may be inferred from the experimentally determined values of impedance circles, it seems probable that a and a' are the complex quantities and that their complexity is due largely to hysteresis effects and eddy currents in the magnetostrictive

core as the dip angle largely disappears when the core is a thin nickel tube split longitudinally.

An extensive experimental study of motional impedance in the case of magnetostriction has been made at this laboratory by Mr. K. C. Black[4] at my suggestion, and is contained in his thesis for the Doctorate of Philosophy deposited in manuscript in the Harvard Library. He is publishing a short account of this investigation in a paper following this in the *Proceedings* of the American Academy.

The results are very remarkable in showing that the magnetostrictive system has a very high efficiency as a converter of electric energy into mechanical motion.

Magnetostrictive Sources of Sound. I have made a number of applications of magnetostriction to the production of sound

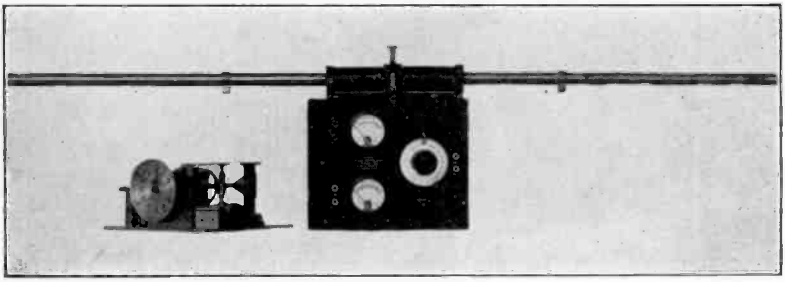

Fig. 15

and ultra sound over a wide range of frequencies. These devices are outside of the scope of the present paper. One application, which is to the measurement of the velocity of sound at various frequencies, is being employed by some of my graduate students in filling in the gaps of the work I previously published[5] in which a piezo-electric crystal oscillator was the radiator of the sound, and the reaction of the reflected sound on the source was the means for indicating nodes and loops of the standing wave system. The frequencies used in those experiments extended from 40,000 to 1,400,000 cycles per second. The use of the magnetostriction vibrators in the same general arrangement of apparatus permits the use of frequencies below the 40,000-cycle

[4] K. C. Black: A Dynamic Study of Magnetostriction, *Proc.* Am. Acad. of Arts and Sci., 63, 49, 1928. These numbers may be purchased separately from the American Academy, 28 Newbury St., Boston, Mass.

[5] *Proc.* Am. Acad., 60, No. 5, 1925.

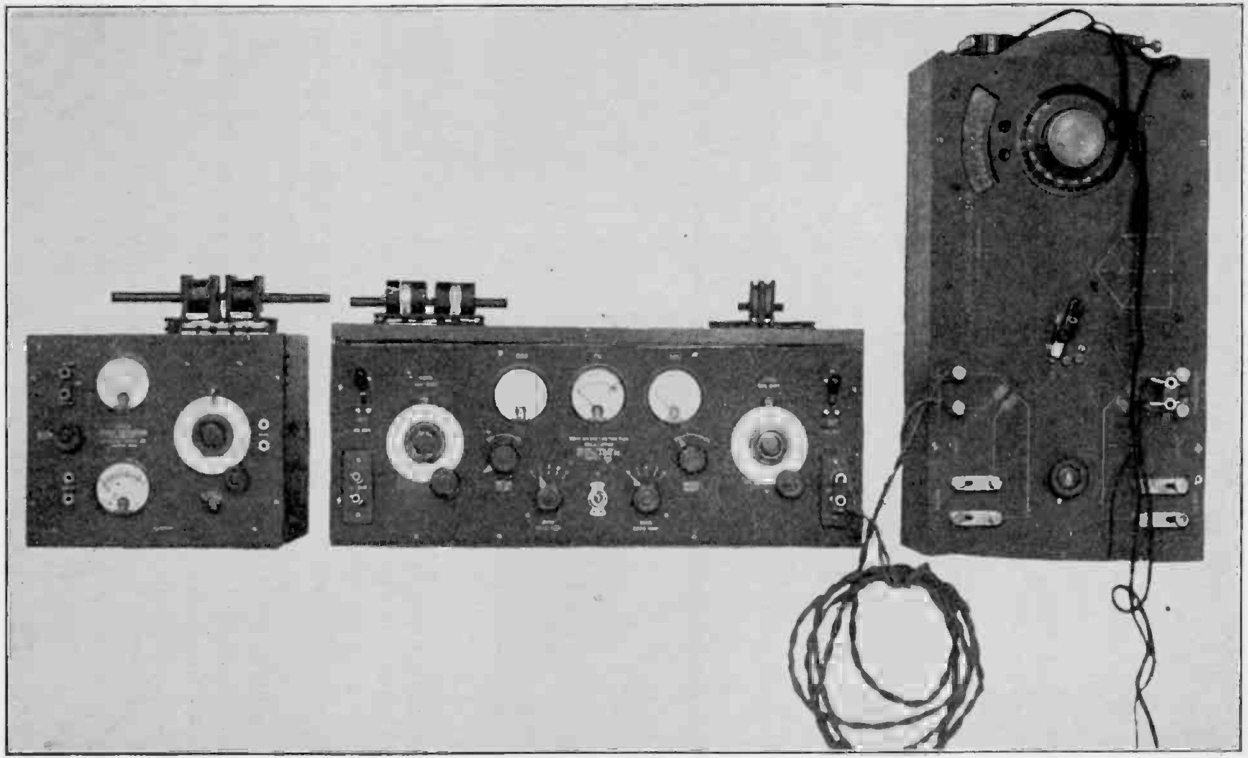

Fig. 16

value, and also, since rods are easily cut to any predetermined frequency, permits filling in certain significant frequencies that were lacking in the previous investigations. Also various gases are being employed in the experiments.

Another sound-velocity application consists in putting various solid non-magnetostrictive rods on the end of a magnetostrictive driving rod, and by means of frequency measurements determining sound-velocity and elastic properties of non-magnetic and other non-magnetostrictive materials. These new investigations are well under way.

Arrangements for Obtaining High Frequencies. In the production high-frequency stabilization by magnetostriction rods I have used three methods. (*a*) One is by the use of very short cylinders, placed within the plate coil with their axes parallel to the magnetic field of this coil; (*b*) another is by flat strips or sheets of the magnetostrictive material placed between the plate and grid coils; and (*c*) by what I may call *beaded rods*. The latter method is probably the best. An illustrative example, shown in Fig. 12, consists of a rod 1.26 cm in diameter and 9 cm long with grooves turned in it to a depth of half the radius. The grooves are 1 cm wide and separated by 1 cm so that the vibrator is in the form of five cylindrical beads, each 1 cm long held in succession 1 cm apart by cylindrical rods of half the diameter of the beads.

When this beaded rod has been annealed and is placed in a coil-pair having 200 turns on each coil, and so positioned that one bead is in one coil and the next bead is in another coil or else one bead between coils, it shows strong stabilization of frequency 295,480 cycles per second. The material is stainless steel with velocity of 5430 meters per second, so the frequency is that of a linear vibrator of length $543000 \div 2 \times 295480 = 0.918$ cm, which is about 10 per cent less than the computed value of one of the beads standing alone and regarded as a linear vibrator. There are other frequencies of the system, particularly one at 19888 cycles per second.

The theory of such a beaded vibrator has been pretty well worked out but to save space is not here given.

For lack of space also the general vacuum-tube theory is here omitted.

In the accompanying appendix a more detailed theory of sound propagation in the magnetostriction rod is presented.

Appendix I

Theory of Dynamic Magnetostriction, Including Theory of Propagation of Sound in a Viscous Magnetostrictive Medium. Referring to Fig. 13, let us consider a rod of length $2l$ wound with a solenoid of N turns per cm.

Let S = area of cross section of the rod. Let x = the distance from the center to any section of the rod, and let us consider a volume of length Δx extending from x to $x+\Delta x$.

Let p_a and y = external pressure and displacement at x of the section Δx, and

$p_a+\frac{\partial p_a}{\partial x}\Delta x$ and $y+\frac{\partial y}{\partial x}$ = the corresponding quantities at $x+\Delta x$,

and let us note that the pressure at x and $x+\Delta x$ are both estimated inward upon the section Δx, while the displacements are both in the x-direction.

Before analysing the external pressure p_a into its components, we may equate the force in the x-direction to the mass × acceleration of the elemental volume Δx, obtaining

$$S\left[p_a-\left\{p_a+\frac{\partial p_a}{\partial x}\Delta x\right\}\right]=S\Delta x\rho\frac{\partial^2 y}{\partial t^2}, \tag{1}$$

in which ρ = density of the material of the volume element.

Performing the operations of (1), dividing by $S\Delta x$ and taking the limit as Δx approaches zero, we obtain

$$-\frac{\partial p_a}{\partial x}=\rho\frac{\partial^2 y}{\partial t^2} \tag{2}$$

Let us now analyse p_a into its constituents; namely, let

$$\begin{aligned} p_a&=p_\epsilon+p_G+p_m, \text{ where}\\ p_\epsilon&=\text{pressure due to elasticity,}\\ p_G&=\text{pressure due to viscosity,}\\ p_m&=\text{pressure due to magnetostriction.}\end{aligned} \tag{3}$$

These various p's are due to the pressures of expansion of an element to the left of that shown in the figure, and are given by the equations

$$p_\epsilon=-\epsilon\left\{\frac{\text{increase of volume}}{\text{volume}}\right\}=-\epsilon\frac{\partial y}{\partial x}, \tag{4}$$

$$p_G = -G\frac{\partial}{\partial t}\left\{\frac{\text{increase of volume}}{\text{volume}}\right\} = -G\frac{\partial}{\partial t}\left(\frac{\partial y}{\partial x}\right), \tag{5}$$

$$p_m = aB, \text{ in which} \tag{6}$$

ϵ = Young's modulus in dynes per sq. cm

G = a viscosity coefficient in *c.g.s.* units

B = magnetic induction at x, producing p_m

a = a coefficient relating expansive pressure of magnetostriction in dynes per sq. cm. to magnetic induction B.

The coefficients ϵ and G are positive, a is positive for some magnetostrictive materials and negative for others. Also a is not exactly constant but varies with B as well as with the material. We shall, however, need to consider it a constant where B is a small induction added to an already existent constant large induction.

The substitution of (4), (5), and (6) into (2) and (3) gives

$$\rho\frac{\partial^2 y}{\partial t^2} = \epsilon\frac{\partial^2 y}{\partial x^2} + G\frac{\partial\partial^2 y}{\partial t\partial x^2} - a\frac{\partial B}{\partial x} \tag{7}$$

and

$$p_a = -\epsilon\frac{\partial y}{\partial x} - G\frac{\partial\partial y}{\partial t\partial x} + aB. \tag{8}$$

We shall now further analyze B. We shall suppose the existence of a steady magnetic induction B_o, which will polarize the system and determine the size of the coefficient a, but will not contribute to p_m, which we shall suppose to be due to an additional periodic B. This additional B is made up of a quantity due to the variable current i in the windings plus an additional quantity B' called into play by magnetostriction as a result of distortion; that is

$$\begin{aligned} &B = B_i + B' \text{ where} \\ &B_i = \text{magnetic induction due to } i \\ &B' = \text{magnetic induction due to expansion of the element} \\ &\qquad \Delta x \text{ and is a function of } x. \end{aligned} \tag{9}$$

This B' we shall assume proportional to increase of length of the element divided by the original length of the element; that is,

$$B' = a'\frac{\partial y}{\partial x} \tag{10}$$

In substituting (9) and (10) into (7) and (8) we shall regard

$$\frac{\partial B_i}{\partial x} = 0 \tag{11}$$

The substitution then gives

$$\rho\frac{\partial^2 y}{\partial t^2} = \epsilon'\frac{\partial^2 y}{\partial x^2} + G\frac{\partial\partial^2 y}{\partial t\partial x^2} \tag{12}$$

and

$$p_a = -\epsilon'\frac{\partial y}{\partial x} - G\frac{\partial}{\partial t}\frac{\partial y}{\partial x} + aB_i \tag{13}$$

where as an abbreviation

$$\epsilon' = \epsilon - aa' \tag{14}$$

Equations (12) and (13) are to be treated as simultaneous.

In solving (12) we shall here restrict the treatment to the case in which the time t enters in y only in a factor of the form $e^{j\omega t}$, where ω is the angular velocity of the current i. This reduces (12) to the form

$$-\rho\omega^2 = (\epsilon' + jG\omega)\frac{\partial^2 y}{\partial x^2} \tag{15}$$

which gives

$$y = e^{j\omega t}\left\{Ae^{kx} + A'e^{-kx}\right\} \tag{16}$$

with

$$k = +j\omega\sqrt{\frac{\rho}{\epsilon' + jG\omega}} \tag{17}$$

We shall next stipulate that the center of the rod has zero motion; that is, $y = O$ at $x = O$. This gives

$$y = Ae^{j\omega t}\sinh kx \tag{18}$$

Now to determine A, we introduce the further boundary condition that $p_a = O$ at $x = l$, so (13) gives

$$O = -(\epsilon' + jG\omega)\frac{\partial y}{\partial x} + aB' \quad \text{at} \quad x = l \tag{19}$$

Replacing y in this equation by its value from (18) we obtain

$$Ae^{j\omega t} = \frac{aB'}{k(\epsilon' + jG\omega)\cosh kl}$$

and consequently by (18)

$$y = P \sinh kx \tag{20}$$

where as an abbreviation

$$P = \frac{aB'}{k(\epsilon' + jG\omega)\cosh kl} \tag{21}$$

Let us now turn to a consideration of the electrical system in which there is a variable current i flowing. The variable emf at the terminals of the coil is

$$e = Ri + \frac{\partial}{\partial t}\{\text{flux linkage of } (B_s + B')\} \tag{22}$$

The first two terms of the right-hand side of this equation give e damped; that is, the value of e if the rod were restrained from vibrating. The last term is the contribution of the motion, and may be called the *motional* emf, so

$$e' = \frac{\partial \phi}{\partial t}, \quad \text{where} \tag{23}$$

e' = motional emf

ϕ = flux linkage of B' with the circuit.

To obtain ϕ, let us note that per unit area of S at any element Δx, distant x from the center, magnetic induction of amount $B' - (B' + \Delta x \partial B'/\partial x)$ leaks out between the turns of wire and these return to the core at distance minus x from the center, and thus link with $2Nx$ turns giving

$$\Delta\phi = -2NSx\frac{\partial B'}{\partial x}\Delta x,$$

where N = number of turns of wire per cm.

To get the total linkage we must integrate this from $x=O$ to $x=l$, and must add $2NSlB_l'$ to account for leakage from the end, obtaining

$$\phi=2NS\left\{-\int_0^l x\frac{\partial B'}{\partial x}dx+lB_l'\right\} \tag{24}$$

We may first integrate this by parts by putting

$$u=x, \quad dv=\frac{\partial B'}{\partial x}dx, \text{ obtaining}$$

$$\phi=2NSl\int_0^l B'dx$$

We may now complete the integral by replacing B' by its value from (10) and obtain

$$\phi=2a'NSy_l, \text{ where} \tag{25}$$

$$y_l=\text{value of } y \text{ at } l$$

By (20) and (21) this gives

$$\phi=2a'NSP\sinh kl$$

$$=\frac{2aa'NSB_i}{k(\epsilon'+jG\omega)}\tanh kl$$

Now returning to the motional emf, equation (23), and noting that the time derivative is $j\omega$ times the quantity, and then replacing $j\omega/k$ by its value from (17), we obtain

$$e'=\frac{2aa'NSB_i}{\sqrt{\rho\{\epsilon'+Gj\omega\}}}\tanh kl \tag{26}$$

If now

L = self inductance of the coil with rod damped, we may write Li = flux linkage of Bi, which is $2NSlB_i$, so

$$B_i=\frac{Li}{2NSl} \tag{27}$$

which substituted into (26) gives

$$e'=Qi\tanh kl \tag{28}$$

In this equation I have introduced as an abbreviation

$$Q = \frac{aa'L}{l\sqrt{\rho\{\epsilon' + jG\omega\}}} \tag{29}$$

Motional Impedance. If we let z' = complex motional impedance of the system, and compare (28) we have

$$z' = Q \tanh kl \tag{30}$$

Equation (30) gives the complex motional impedance of the system; Q and k are defined by (29) and (17), respectively.

To investigate the manner in which z' varies with ω, we may note that while Q involves ω, the term in which the ω appears is comparatively small, and since the whole motional action is confined to a very small range of ω, we may regard Q as a constant.

Let us now write[6]

$$k = \alpha + j\beta, \text{ where} \tag{31}$$

$$\alpha = \omega\sqrt{\frac{\rho}{\epsilon'(1+h^2)}}\,g(h) \tag{32}$$

$$\beta = \omega\sqrt{\frac{\rho}{\epsilon'(1+h^2)}}\,f(h) \tag{33}$$

$$f(h) = \sqrt{\frac{\sqrt{1+h^2}+1}{2}} \tag{34}$$

$$g(h) = \sqrt{\frac{\sqrt{1+h^2}-1}{2}} \tag{35}$$

$$h = G\omega/\epsilon' \tag{36}$$

Introducing the value (31) for k into (39) and breaking z' into its resistance and reactance components, R' and X', we have

$$z' = R' + jX' = Q\frac{\sinh(\alpha + j\beta)l}{\cosh(\alpha + j\beta)l}$$

[6] Regarding the functions $f(h)$ and $g(h)$ see G. W. Pierce: "A Table and Method of Computing Electric Wave Propagation, Transmission Line Phenomena, Optical Refraction, and Inverse Hyperbolic Functions of a Complex Variable", *Proc.* Amer. Acad., 57, No. 7, 1922, where a table of the functions f and g is given for a large range of values of h.

which after expansion and rationalization becomes

$$R'+jX'=Q\,\frac{\sinh \alpha l \cosh \alpha l + j \sin \beta l \cos \beta l}{\sinh^2 \alpha l + \cos^2 \beta l}$$

From this we may obtain

$$R'^2+X'^2=2R_oR', \text{ where} \tag{37}$$

$$2R_o=Q\,\frac{\sinh^2 \alpha l + \sin^2 \beta l}{\sinh \alpha l \cosh \alpha l} \tag{38}$$

Equation (37) is in the form of the equation of a circle of radius R_o. Equation (38) shows, however, that R_o involves the variable parameter ω so (37) is not a true circle. Nevertheless, in the case of the magnetostrictive system, the resonance is so sharp that the whole phenomenon of motional reactance is exhibited within a frequency range of a fraction of one per cent of the resonant frequency; so the variation of the coefficient R_o is inappreciable to the limit of the errors of the experimental measurements that Dr. Black has made.[7]

[7] K. C. Black, "A Dynamic Study of Magnetostriction," *Proc.* Amer. Acad., **63**, 49; April, 1928.

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THE IMPORTANCE OF RADIOTELEGRAPHY IN SCIENCE*

By

Jonathan Zenneck

(President, Institute of Technology, Munich, Germany)

When discussing today what science owes to radiotelegraphy I feel that I must first apologize for having selected so general a subject. While most papers read before this Institute refer to special problems of radiotelegraphy proper, in view of the somewhat extraordinary character of this meeting I hope that an exception to this rule may be permitted, since I am not a professor of radiotelegraphy but of general experimental physics.

There is no doubt that the splendid development of radiotelegraphy itself would be the most attractive theme for a paper, so attractive indeed that it has almost become the standardized subject of addresses to be delivered before radio meetings. Having for a long time been a member of your Committee on Standardization I certainly appreciate standardization, but when it comes to papers, I prefer individual production.

After touching upon the development of radiotelegraphy let me say a few words on the "romantic period in the radio field," as Dr. Alfred N. Goldsmith put it in his Presidential address, and let me refer to it in a somewhat romantic manner. In 1900 we were very proud when, in experiments on the North Sea with a Braun transmitter, we had succeeded in establishing "wireless communication" between the isle of Heligoland and the coast, a distance of some thirty miles. Please do not ask questions as to what "wireless communication" meant at that time. Just believe me that what we had was no worse nor better than anything then given the grand name of wireless communication. Our aim was to get 100 miles. Very soon this was attained by us and by others, and as distances at which wireless messages could be transmitted gradually increased, the goal was pushed further and further, and finally the ideal of enthusiastic wireless men became πR, where π means the cyclic number and R the radius of the earth. In other words, they dreamt of a

* Dewey decimal classification: R010. Original manuscript received by the Institute, August 28, 1928. Delivered before New York meeting of the Institute, September 5, 1928.

wireless communication with the Antipodes, just as some enthusiasts are dreaming now of rocket airship traffic with the Moon. Then came the time when radio communication with the Antipodes was established by means of short waves with much less power than anybody would have thought of. This result was greatly deplored by all true radio enthusiasts because no further record seemed to be possible, since for mathematical and geophysical reasons, respectively, neither π nor R could be increased. But wireless telegraphy went beyond this limit which nature seemed to have put to any further extension. All of you know that it has become possible to receive radio waves which have travelled at least twice around the earth. All this sounds like a romance, but it is not. With what has been achieved since Hertz's laboratory experiments and Marconi's invention up to the present time, radiotelegraphy means a development unrivaled in the history of natural and technical science.

But I do not want to dwell upon that any longer. What I want to do is to illustrate by a number of examples the influence which this development of radiotelegraphy has had on science and, in the first place, on physics, the mother of wireless telegraphy.

I.

I have to begin with that domain of physics in which wireless telegraphy was raised and which naturally first felt the influence of the new art,—I mean the theory of oscillations.

The old equation of Kirchhoff and Lord Kelvin:

$$L\frac{di}{dt}+Ri+\frac{1}{C}\int i\cdot dt=e$$

determining the free or forced oscillations of a circuit respectively depending on whether or not the impressed emf e is equal to zero, still holds. But owing to the experience gained in radiotelegraphy we know that this equation covers possibilities never thought of at the time when it was developed. At that time it would have been almost absurd to mean by L, R, and C anything but constants of the circuit independent of the current in it. Thus for free oscillations the result was $i=Ie^{-\delta t}\sin(\omega t+\alpha')$ i.e., an oscillation having the cyclic frequency $\omega=1/\sqrt{LC}$ and an amplitude decreasing with time according to an exponential law. For dozens of years this was considered the only solution to the above equation.

But very soon after the beginning of radiotelegraphy, at the time when the transmitters with their crashing and blinding sparks appeared to be more nearly lightning factories than technical apparatus, there arose some doubt as to whether the previously mentioned solution held for circuits including a spark gap. It was at least not self-evident that the energy absorbed by a spark during a time element dt should be determined by the

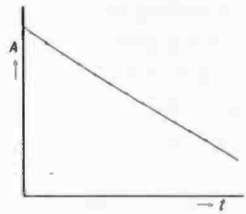

Fig. 1 —Decay of Amplitude in Circuit Including a Spark.

same law as that in an ohmic resistance and hence could be expressed by a term Ri^2dt, where R is a constant. By means of a Braun cathode-ray tube the author made careful measurements with a circuit containing a spark gap and very little ohmic resistance, and plotted the amplitude of its oscillations against time. I found a curve like that in Fig. 1, which is copied from my original paper[1] and which shows that the decay of amplitude

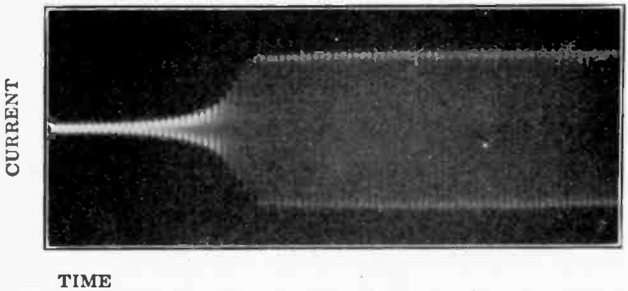

Fig. 2—Increase of Current at Closing an Arc Generator.

follows a linear rather than an exponential law, which means that in a circuit containing a spark the term R cannot be regarded as a constant.

Interesting as this may have been from a physical point of view, practically it does not make much difference whether the amplitude decreases according to a linear or an exponential

[1] J. Zenneck, *Ann. Phys.*, **13**, 822, 1904.

law. When, however, the arc and tube generator came into view, it meant radically new and hitherto unthought-of possibilities. If, for instance, the circuit of an arc generator is closed we get in the circuit an oscillatory current as shown in the oscillogram of Fig. 2 (which the author took a long time ago with a Braun tube[2]); and the corresponding curves for a tube generator are very similar. From such curves it is seen that the amplitude first increases and finally reaches a constant value. If we maintain, at least formally, our equation above, the resistance term R has first a negative value, which gradually decreases to zero. If some thirty years ago someone had proposed to discuss the above equation under the assumption of a negative resistance R, it may be that a mathematician would have been willing to do so, because it is irrelevant to him whether a term has a posi-

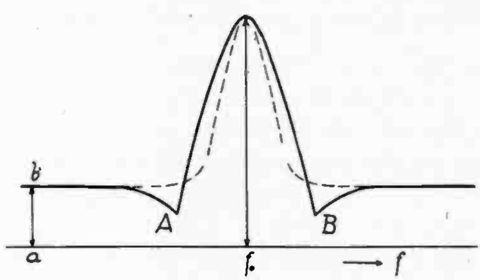

Fig. 3—Resonance Curve of a Tube Generator when Impressed by an emf of Constant Amplitude but Variable Frequency f.

tive or a negative sign. But I am sure that a physicist would have indignantly refused to consider a negative resistance which he would have looked upon as a physical absurdity. In the meantime we have learned that in an oscillatory circuit, when properly connected to an arc or tube, the energy delivered may exceed that absorbed in the circuit and that we might well bring such a circuit within the scope of our equation by attributing to it a negative resistance the value of which decreases with increasing amplitude of the current.

Moreover, if in such a circuit with self-sustained oscillations of frequency say f_0 an emf is applied, the frequency f of which is being gradually varied, we expect to get in the system two oscillations, one being the self-sustained free oscillation of constant frequency f_0 and another the forced oscillation of the variable frequency f. We further expect that the effective value of

[2] J. Zenneck, *Ann. Phys.*, **43**, 481, 1914.

the current will be the resultant of the two oscillations and therefore that the resonance curve will have the shape of the dotted curve in Fig. 3, where *ab* corresponds to the effective value of the sustained oscillations of frequency f_0. What we actually get[3] is the solid curve of Fig. 3. When we examine the frequency of the oscillations produced we find that between the points A and B there are no free oscillations of frequency f_0, but only forced oscillations of the variable frequency f. This phenomenon is well-known in oscillating audion reception. As Dr. B. van der Pol[4] has shown, it may be interpreted as another result of a resistance the sign and value of which depend upon the amplitude of the current.

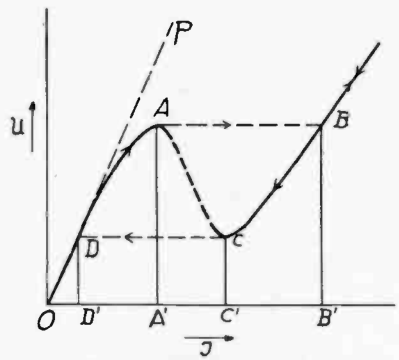

Fig. 4—Voltage-Current Characteristic of a Circuit Containing a Closed Iron Core.

In addition to systems with variable resistance we have to deal with circuits of variable inductance such as those containing an iron core as is used in magnetic frequency changers. Now, in a circuit with constant resistance and inductance the voltage-current characteristic of forced oscillations is determined by

$$u = i\sqrt{R^2 + j\left(\omega L - \frac{1}{\omega C}\right)} \qquad (8)$$

giving a straight line such as the dotted line OP in Fig. 4, when the impressed emf u is plotted against the current. Instead of that, the characteristic of a circuit containing an iron-core coil has the form of the solid curve of Fig. 4. It exhibits a materially

[3] Vincent, *Proc.* Phys. Soc. London, 32, 84, 1920; F. Rossmann and J. Zenneck, *Jahrb. d. Draht. Tel.*, 24, 47, 1924.

[4] B. van der Pol, Jr., *Tijdschr. Nederl. Radiogenootschap*, 2, 56, 1924; *Phil. Mag.* (7) 3, 65, 1927.

new effect[5] which is easily seen when we gradually increase the voltage. Up to the value AA' the current also gradually increases, but when the voltage exceeds this value by a small amount, the current suddenly jumps from the value OA' to the much higher value OB'. This effect which we call *kipperscheinung* (unbalance or instability effect) may be very dangerous, since the heavy current and the correspondingly high voltages at the inductance and condensers may be damaging to the plant. In 1915 when making our first experiments with the machine transmitter at Sayville, in which magnetic frequency changers were used, we got this effect. I well remember how frightened we were when our ammeter suddenly jumped to about double the normal value after we had increased the voltage by an inappreciable amount. We also saw that when the value of the

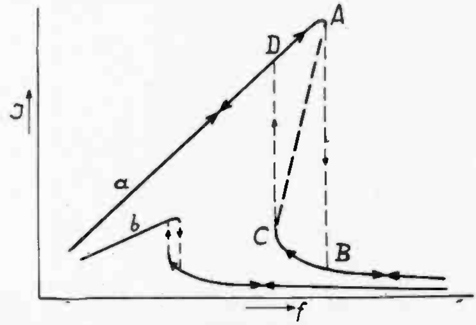

Fig. 5—Resonance Curves of a Circuit Containing a Closed Iron Core when Impressed by an emf of Constant Amplitude but Variable Frequency *f*.

impressed voltage was kept constant while its frequency was gradually varied, we got resonance curves of the kind drawn in Fig. 5 for two different voltages. In consequence of this experience and in order to avoid trouble caused by our lack of knowledge of the working conditions of such a transmitter, I tried to treat the matter theoretically and on September 1st, 1915, almost exactly thirteen years ago, I read a paper before this Institute on "A Contribution to the Theory of Magnetic Frequency Changers" in which I reported the results of my theoretical investigation.[6]

[5] O. Martienssen, *Phys. Zeits.*, **11**, **448**, 1910. H. Schunck and J. Zenneck, *Jahrb. d. Draht. Tel.*, **23**, 63, 1924.

[6] J. Zenneck, Proc. I. R. E., **8**, 463, 1920. Paper read before the Institute, September 1, 1915.

In a loaded frequency changer, we are of course concerned with coupled circuits. The situation with coupled circuits also has changed materially since pre-radio times. The very fundament of previous coupling theory has been touched upon. Take for instance inductive coupling such as shown in the upper part of Fig. 6. It consists of an

$$\text{emf} = -L_{12} \cdot \frac{di_1}{dt}$$

impressed on the secondary from the primary circuit and of a reactive

$$\text{emf} = -L_{21} \cdot \frac{di_2}{dt}$$

induced in the primary. Now, in every textbook of physics you find as a basic relation

$$L_{12} = L_{21}$$

Generally speaking, this means that whenever conditions are such as to produce a strong effect by the primary on the secondary circuit, it necessarily implies a strong reaction of the secondary on the primary. This, of course, does not hold today. As far as I am aware Mr. Armstrong[7] was the first to call attention to the fact that by coupling two circuits through an amplifier

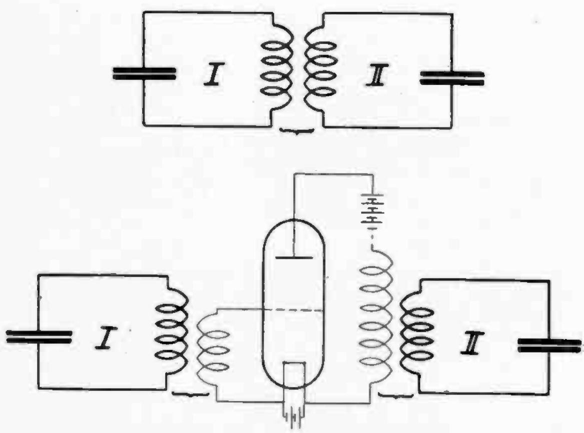

Fig. 6—Upper Part: inductive coupling of two circuits. Lower Part: inductive coupling of two circuits through an amplifier tube.

[7] E. H. Armstrong, Proc. I. R. E., 5, 145, 1917.

tube, as shown in the lower part of Fig. 6, it is readily possible to have the secondary circuit strongly influenced by the primary without at the same time experiencing any appreciable reaction from the secondary on the primary.

Furthermore it is a well-known result of the theory of tuned coupled circuits, that when the coupling is tight, in the primary as well as the secondary circuit, the same two coupling oscillations appear. Since the frequencies of these two oscillations are different, the time curves of the primary and secondary currents

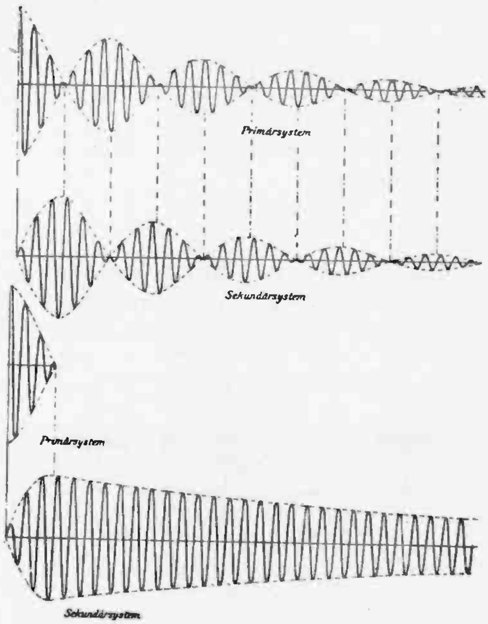

Fig. 7—Upper Curves: damped oscillations in two tightly coupled circuits. Lower Curves: damped oscillations in two tightly coupled circuits, the primary including a quenching gap.

are of the forms of the first and second curves respectively in Fig. 7. We have known for a long time that we may get a totally different effect, as represented by the third and fourth curves in Fig. 7, if in the primary circuit, instead of an ordinary spark gap a proper quenching gap, such as the mercury vapor lamp of Cooper Hewitt or the extremely short gap of M. Wien, is used. In such a case the function of the primary circuit is almost exclusively to excite, by a kind of impulse, the free oscillations of the secondary circuit.

Some years ago a new form of impulse excitation came up—the magnetic synchronized impulse excitation—in the secondary circuit of which almost undamped oscillations of a frequency much higher than that of the primary circuit may be produced.

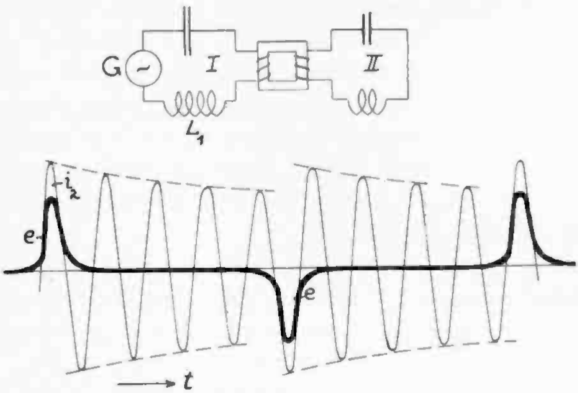

Fig. 8—Magnetic Synchronized Impulse Excitation.

For this purpose in the primary circuit (I, Fig. 8) containing the alternator in addition to a large air-core inductance L_1, the primary of an iron-core transformer is inserted, the iron of which becomes highly saturated by the current used. In this case the

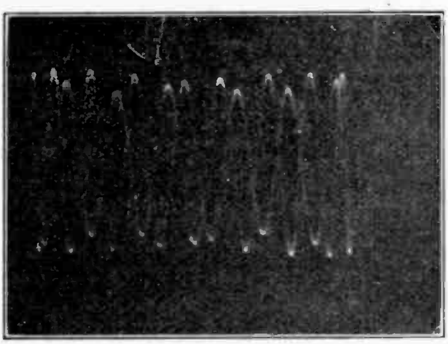

Fig. 9—Magnetic Synchronized Impulse Excitation. Secondary current plotted against primary current.

emf induced in the secondary (II, Fig. 8) circuit is of the form of the heavy curve e of Fig. 8. If, then, the secondary circuit is tuned to a high odd multiple of the primary frequency, its oscillations as shown by curve i_2 in Fig. 8 receive a new impulse twice per period of the primary circuit, and in the meantime between two

impulses are falling off according to the decrement of the circuit. If this decrement is small or if special means are employed to offset the effect of the natural decrement, almost undamped oscillations in the secondary circuit are produced. This is best proved by the photograph of Fig. 9, a Lissajou figure taken on such a device with a Braun tube, where the secondary current of 15 times the frequency of the primary is plotted against the primary current. In this photograph the damping of the secondary oscillations is noticeable but very small. Incidentally, this photograph with its well-defined clean-cut curve may show you that we have developed the technique of the Braun cathode-ray tube fairly well.

Since the output of the device just mentioned is a current of much higher frequency than that delivered by the alternator, the device may be and generally is considered one for frequency

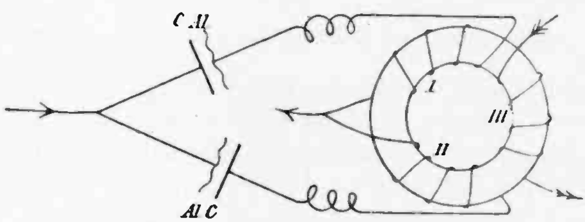

Fig. 10.—The Author's Device for Frequency Doubling.

multiplication. Multiplication of frequency is another field which radiotelegraphy has contributed to the province of oscillations. As far as I am aware, I was the first to disclose the idea of frequency multiplication by static frequency changers. In one of the weekly meetings in the physical laboratory of Professor Braun the advantages of undamped waves for radiotelegraphy had been discussed. There was general agreement that at the time it seemed hopeless to think of generating such oscillations of sufficiently high frequency by an alternator. After this meeting it occurred to me that it might be possible to multiply the frequency of a given alternating current and in a paper[8] which was published in 1899 under the heading "A Method for the Transformation of Frequency by Means of A Static Transformer," I described the arrangement of Fig. 10 which is taken from the original paper. The primary current was divided into two

[8] J. Zenneck, *Ann. Phys. Chem.*, 69, 858, 1899.

branches, each containing an electrolytic valve (the only electric valves then known to me) and a coil, both coils being wound on the same iron core. I showed by oscillograms taken with a Braun tube that in a third coil wound on the same core a current of double frequency was produced. Of course my arrangement had very poor efficiency, but as was frequently the case in radiotelegraphy, when an idea was once proposed, the problem of its realization was attacked upon a number of different lines. Thus some years later I. Epstein described[9] the well-known arrangement of Fig. 11 for frequency doubling. In this system the magnetic properties of an iron-core coil with direct-current saturation are employed. For a dozen years this method has been

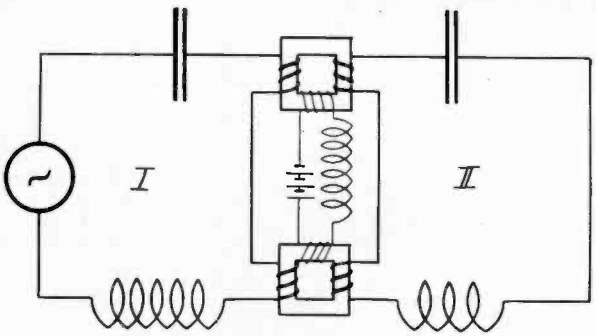

Fig. 11—Epstein's Device for Frequency Doubling.

in constant use for the transatlantic radio service of Nauen and many other commercial stations, including that at Sayville, Long Island from 1915 to 1917.

Now frequency multiplication is but one instance of the interesting frequency situation as generated by the needs and means of radiotelegraphy. That in addition to a frequency multiplication a frequency demultiplication or frequency division should be possible will be obvious to anybody who knows that, mathematically, division is the inversion of multiplication, and who is not aware of how difficult it is sometimes to get the physical equivalent of a mathematical operation. I may refer in this connection to the above-mentioned problem of reversing the sign of a resistance. As a matter of fact present conditions are such that a current of a given frequency may be changed into one of any other frequency. Not only are we able to filter out

[9] J. Epstein, *DRP*, 245; 445 (1903).

of the oscillations generated by a low-frequency source its high-frequency harmonics, or to produce a low-frequency current by beating two high-frequency oscillations, but we also have means for passing from one audio frequency to another by means of modulating, filtering, and heterodyning radio-frequency currents. I wonder if in the near future music will take advantage of this possibility. For instance by using such a frequency changing device and a loudspeaker a bass singer may, if needed, appear as a tenor or when a flautist should play a number in A flat major which is very uncomfortable on a flute, he might well play it in D major which is much easier and then by a frequency-changing device and loudspeaker transpose it into A flat major.

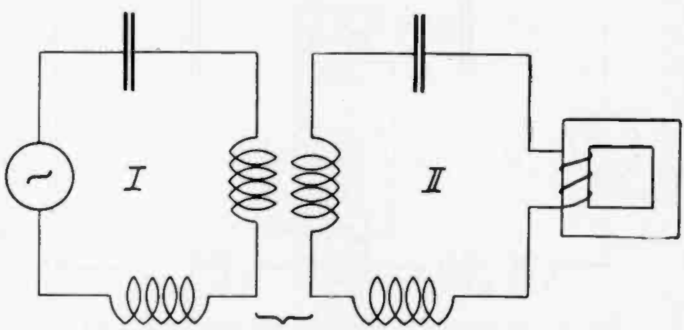

Fig. 12—Circuit Arrangement for Producing Self-modulated Oscillations.

Before leaving frequency changers and coupled circuits I would like to mention a curious effect[10] produced by the harmless-looking arrangement shown in Fig. 12, in which two circuits are tightly coupled, the primary containing the generator, the secondary a coil with closed iron core. Such a device may give currents as shown in the Braun tube oscillograms of Fig. 13. The primary as well as the secondary current seems to have been automatically modulated. This may be of interest for the following reasons: whenever a generator of constant frequency and constant amplitude acts upon a system of circuits it is a general assumption that whatever conditions may be, the currents in these circuits will have constant amplitude, at any rate after the transient phenomena have disappeared. This as-

[10] K. Heegner, *Zeits. f. Phys.*, **29**, 91, 1924. H. Plendl, F. Sammer, and J. Zenneck, *Jahrb. d. Draht. Tel.*, **26**, 104, 1925.

sumption is expressed by putting the current in any of the circuits in the form

$$i = Ie^{-j\omega t}$$

That there are cases where this almost self-evident assumption does not correspond with the fact is shown by the experiments just mentioned.

These examples may be sufficient to demonstrate how far, compared with the classic theory of oscillations, our knowledge in this field has been extended by the problems and experiences met with in radiotelegraphy.

II.

At least as important as the suggestions and problems which physics was given by radiotelegraphy are the instrumentalities which radiotelegraphy added to the experimental resources of physics.

All of you know how troublesome it was to measure a weak alternating current. While it is a simple matter to measure a direct current of the order of 10^{-9} ampere by a moving coil galvanometer, or even one of the order of 10^{-11} or 10^{-12} ampere with an armored fixed-coil galvanometer having an astatic system, the best we had for the measurement of feeble alternating currents was the vacuum thermo-couple used with a sensitive direct-current galvanometer. Compared, however, with the present means for measuring direct currents this method is extremely insensitive. Nowadays radiotelegraphy has furnished us with means such as good crystal detectors, Fleming valves, De Forest audions, and all those methods known as tube ammeters and voltmeters which have made measuring weak alternating currents and voltages a pleasure.

In addition to rectifiers for feeble currents radiotelegraphy has provided high-vacuum rectifiers for heavy loads such as the Kenotron of the General Electric Company. The modern Roentgen ray methods are made use of extensively to produce direct currents of extremely high voltage needed for operating present day Roentgen ray tubes. These rectifiers have entirely superseded the old synchronous mechanical commutators which were formerly used for rectifying alternating current of high voltage. I am sure that no one working in a physical laboratory will regret the disappearance of this apparatus as the sparks and the

undesired oscillations they excited in all more or less nearby conductors were about as welcome in a physical laboratory as hail in a corn field. And modern Roentgen ray tubes themselves, with their high vacuum and their heated cathodes such as those developed by Dr. Coolidge, have grown in the same field where the electron tubes of radiotelegraphy were raised.

Coming now to the electron tube as an amplifier I am almost afraid to say anything. So general has become its use in experimental physics that when we talk of a tube we mean an amplifier tube, and when we mention an amplifier, everyone understands that we mean a tube amplifier. When we read a paper on an

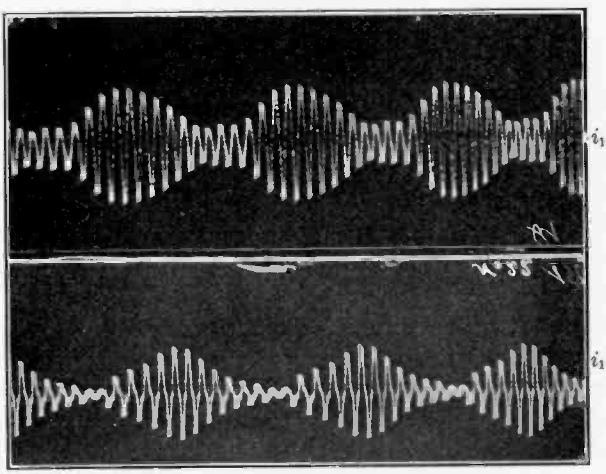

Fig. 13—Primary and Secondary Circuit as Produced by the Device of Fig. 12.

experimental investigation we are greatly astonished if no amplifier tube is used. As a matter of fact with the amplifier tube the experimental situation has become such that almost any effect, feeble as it may be, can be amplified to such a degree as to be measured, oscillographed, made audible or visible. A few instances may illustrate that.

In the photometry of stars, by means of the photoelectric cell, direct currents of the order of magnitude of 10^{-14} ampere have to be dealt with. According to experiments made by H. Rosenberg[11] it is possible without appreciably affecting the proportionality between light intensity and current to amplify these

[11] H. Rosenberg, *Berl. Ber.*, 53, 716, 1920.

currents about 100,000 times, so as to measure them by a moving coil galvanometer.

For dosing Roentgen rays it is common practice to measure the current produced by them in an ionization chamber. These currents are of the order of magnitude of 10^{-12} ampere. Commercial apparatus is now being built[12] in which, by a single 4-electrode tube, these currents are amplified and then measured by a direct reading moving coil galvanometer with a sensitivity of 2.6×10^{-7} ampere per scale division. Such apparatus can be handled by any physician while the former electrometric method for measuring these ionization currents was too complicated to be left to a regular doctor.

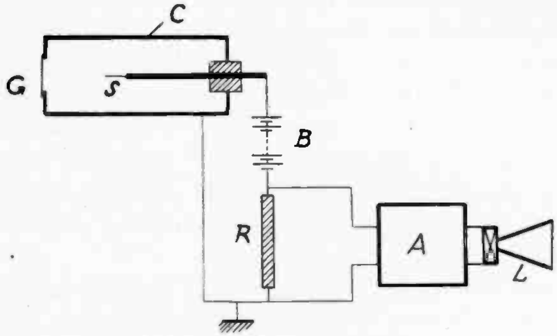

Fig. 14—Geiger Counter.

Another example is the arrangement of Fig. 14 representing the well-known Geiger counter, a metallic cylinder C closed at the front by a mica disk G, in the interior of the cylinder and insulated from it a metallic point S such as a sewing needle, between the point and the cylinder a battery B and a high resistance R, connected between the grid and filament of the first tube of a multi-stage amplifier A, the output of which is fed into a loudspeaker. The voltage of the battery is such that no glow discharge is started between the point and the cylinder. If now a radioactive substance emitting alpha particles is placed near the mica disk, a very loud and sharp crack is produced in the loudspeaker every time an alpha particle is shot through the disk into the interior of the chamber, ionizing the air in it. If Roentgen rays are sent into the cylinder, a great

[12] K. W. Hausser, R. Jaeger, and W. Vahle, *Wissensch. Veröffentl. des Siemens-Konzerns*, 2, 325, 1922.

number of cracks are heard corresponding to the separation of electrons from the atoms and their ionization effect. This experiment, which may be made easily in even a large lecture room, represents an interesting acoustic analogue to the well-known experiments of C. T. R. Wilson, by which these effects are made visible.

To take still another example, if the magnetization of a steel bar or steel needle is reversed, the change in magnetization does not take place gradually, but in small steps when, according to Ewing's view, groups of magnetic elements—whatever they may be—tilt over. This effect may be made audible in a large lecture room by an arrangement due to Barkhausen.[13] The steel needles or bars are placed in a coil with a large number of turns; connected to this coil, through a multi-stage amplifier, is a loudspeaker. If now a strong permanent magnet is moved along the coil and steel bars, a roaring is heard in the loudspeaker owing to the discontinuous change in magnetization. I have mentioned these two last devices in order to show how, by means of an amplifier, elementary processes have been made directly accessible, the existence of which could hitherto be inferred only from their integral effect.

The most wonderful achievement in radiotelegraphy in my opinion is the tube generator. In stating that, I do not think of detracting from the merits of those who, following the steps of Nikola Tesla, built alternators for the production of undamped oscillations. On the contrary I feel that these alternators, together with their frequency-controlling devices such as those of Mr. Alexanderson, represent the most ingenious products of the electrical art. I also fully appreciate V. Poulsen's arc generator which with extreme simplicity combines the possibility of very large units. From the very beginning of radiotelegraphy it was a dream of all connected with it, to be able to work with undamped oscillations. In view of the apparent advantages of such oscillations the problem of generating them was tried from all possible lines of attack. I do not think that twenty years ago anyone would have dared to dream of a generator such as the tube generator which, with relatively simple apparatus, would produce undamped oscillations up to a frequency of 30,000,000 per second or more with a constancy of amplitude and frequency unsurpassed by any other generator, and which when required could be modulated very easily by an audio-frequency current.

[13] H. Barkhausen, *Phys. Zeits.*, 20, 401, 1919.

Of course I am aware that I am not quite correct in saying that the constancy in frequency of the tube generator is unsurpassed by any other generator. As a matter of fact it is surpassed by the tube generator itself when combined with a piezo-electric quartz crystal. I do not desire to dwell upon the practical aspect of this contribution to radiotelegraphy by Professor Cady.[14] What I want to emphasize is its importance from a general point of view. Piezo electricity is one of those physical phenomena which was considered more or less a curiosity even by physicists. Just as in the case of electron emission from hot wires some thirty years ago no physicist, and surely no engineer, would have believed that it would ever be of any practical use. We know now that this phenomenon of piezo electricity has led to an electric oscillator of most valuable properties. It is one of those instances I refer to in warning engineering students in my lectures against the idea that this or that physical phenomenon will never be of practical use and that for this reason they may themselves refrain from being interested in it. Furthermore by the piezo-electric oscillator it has been demonstrated that crystals may be capable of mechanical or elastic vibrations of a frequency of the order of some millions per second and of a decrement as low as 0.0001. I am convinced that no physicist would have believed that this would be possible. I freely confess that if before the piezo-electric oscillator was developed, a gentleman had come to my laboratory and had told me that he had made an invention by means of which it was possible to excite elastic vibrations in a quartz crystal up to a frequency of some millions per second, I would have treated him very politely but would have recommended that he see a doctor.

To come back to the tube generator, I need not tell you that for radio-frequency measurements it has become the only oscillator which is now used. It is especially valuable in connection with Professor R. A. Fessenden's heterodyne principle, not in the original form but in one adapted to this oscillator. As a matter of fact, any minute change in almost any physical property may be detected and measured by this method, since it is practically always possible by this change to influence the frequency of a tube oscillator and thus vary the beat frequency produced by the interaction of this oscillation with one of constant frequency. For instance it is obvious that by this method

[14] W. G. Cady, Proc. I. R. E., 10, 88, 1922.

the dielectric constant of gases, as dependent upon pressure, may be determined readily by simply putting the condenser of the variable generator into the gas, or by making one plate (*B*, Fig. 15) of the condenser movable; extremely small displacements of it may then be measured. This scheme as represented

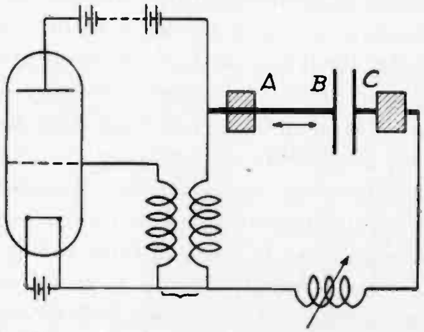

Fig. 15—Device for Measuring Small Displacements.

in Fig. 15 was worked out by R. Whiddington.[15] He succeeded in measuring displacements of the order of 10^{-8} cm, that is, of the dimension of atoms. This means an accuracy far beyond that obtained by light interference methods. That by a similar arrangement a small extension by heat of any solid material,

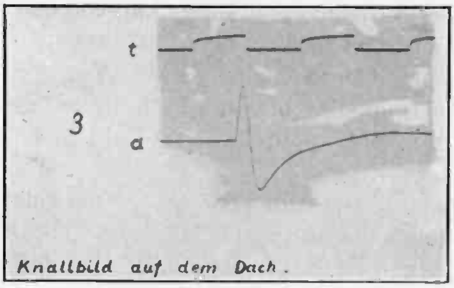

Fig. 16—Curve *t*: time marks of 1/32 sec. Curve *a*: time curve of air pressure in shock test.

that small rotations of parts of seconds of angle,[16] that minute movements of the beam of a highly sensitive balance[17] may be measured, is evident. I only mention it to demonstrate the wide scope of this method.

[15] R. Whiddington, *Phil. Mag.*, 40, 634, 1920.
[16] A. Pflüger, *Phys. Zeits.*, 22, 73, 1921.
[17] F. Kock and G. Schweickert, *Phys. Zeits.*, 23, 123, 1922.

III.

One of the most striking consequences of radiotelegraphy is the revival of the study of acoustics. For a long time this study had been somewhat discredited, so that a physicist working in this field was suspected of failing to find an important problem. This situation has been entirely changed. On one hand, radiotelegraphy has brought up new acoustical problems such as the proper construction of rooms for broadcasting studios, the design of good microphones and loudspeakers. On the other hand, radiotelegraphy has supplied physical and physiological

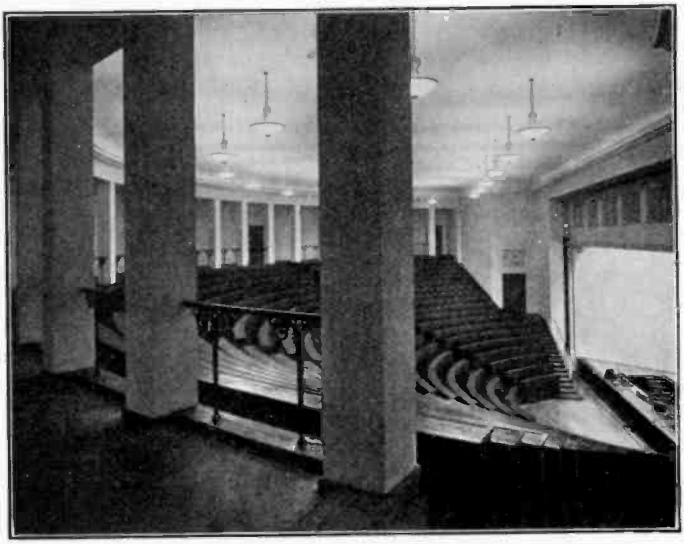

Fig. 17—Lecture Room for Physics at the Institute of Technology in Munich.

acoustics with new experimental means, with its tube generators, its amplifiers, and its high-grade microphones. Thus it became possible to attack successfully problems which a long time ago had been abandoned as practically hopeless, such as the problem of experimentally determining and, if necessary, improving the acoustical properties of a room. To illustrate this I would like to report briefly on experiments[18] made at my suggestion by two of my pupils, Messrs. Scharstein and Schindelin. For the acoustical investigation of rooms we used two methods. In the first method, which we called the shock test, a shot was fired from a

[18] To be published soon in the *Ann. Phys.*

small 22-calibre pistol and the time curve of the air pressure at some point in the room was registered by means of a Reiss microphone, a multi-stage amplifier with resistance-capacity coupling, and a Siemens oscillograph. The curve received in free air, that is, on the roof of my laboratory, was that reproduced in curve 3*a* of Fig. 16. In the second method, which we called the tone test, an audio-frequency tube generator with a loudspeaker in connection with a rotary interrupter sent out groups of tones at regular intervals, and again the time curve of air pressure as produced by this tone group in the room to be investigated was oscillographed.

I want to show you two results. The first is that of the shock test of my lecture room, a photograph of which is shown in Fig. 17 and an elevation in Fig. 18. As you see from the photo-

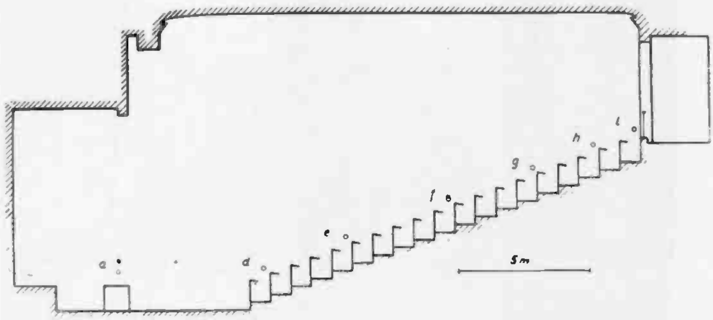

Fig. 18—Elevation of the Lecture Room of Fig. 17.

graph the room resembles an amphitheater of very simple geometrical form. In carrying out the shock test of this room, the pistol was fired at about the geometrical center of the room, i.e., at point *a* of Fig. 18 and close to it was the receiving microphone. The oscillogram as produced in the empty lecture room is that of the second curve in Fig. 19 while the first and third curves represent time marks of 1/32 of a second given by a tuning-fork interrupter. There is to be seen in the oscillogram first the direct shot then the reflections from each row of benches, that from the first row with maximum and those from the others with decreasing intensity, and finally the reflection at the gallery. In the full lecture room as shown by the fourth curve in Fig. 19, the reflections at the benches almost disappear because of the disturbing effect of the students sitting on the benches. There is

only left that at the front of the first bench and that at the gallery. In view of the accuracy with which all details of such a room are reproduced in the oscillogram, it almost might be called an acoustic photograph although this expression might be seriously objected to from a philolgical point of view. The great advantage of this shock test is that from the time interval between the direct shot and its reflection sometimes in connection with the directive property of the pistol shot, it is possible even in complicated cases to place with great exactness that portion of the room in which a reflection takes place and which may be the source of a disturbing echo in the room. Considering the precision of such measurements, a few weeks ago we had a very curious experience. I received a letter from the University

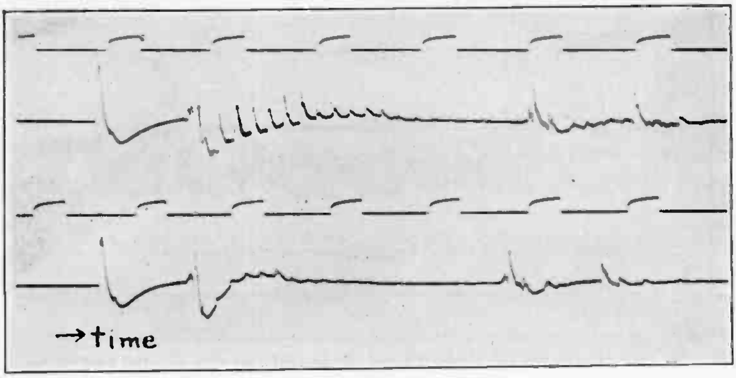

Fig. 19—Oscillogram of Shock Test in the Lecture Room of Fig. 17.

of Freiburg in Baden asking if it was not possible to find out the reason for their auditorium having extremely poor acoustical properties. I sent the above-mentioned engineers there, and they first made a shock test of the auditorium. Their oscillograms showed strong reflections. When, however, they tried to locate the reflecting surface by comparing the time intervals with the plan of the auditorium they met with serious difficulties. They repeated their experiments after having checked their tuning-fork interrupter, but got the same results. Finally they began to doubt the correctness of the plans and measured the main dimensions of the auditorium. They found that the r acoustical measurements had been correct but the plan was inaccurate. Thus, having the correct dimensions, it was easy to find the reflecting surfaces.

As an example of a tone test I have reproduced in curve 1*a* of Fig. 20 the oscillogram obtained at the studio of the broadcast transmitter in Munich, while curve 1*t* gives the time marks and curve 1*b* the current in the loudspeaker. The oscillogram shows only one weak reflection following the direct sound at a very short interval. The tone groups are clearly separated from each other, corresponding to the relatively good acoustic properties of the room. In strong contrast thereto is the corresponding oscillogram—(curve 2*a*)—taken in a hall of the Institute of Technology at Munich, having an arched stone ceiling and a stone floor. The oscillogram clearly exhibits the very bad acoustic properties of the room, the tone groups being completely mixed up; with

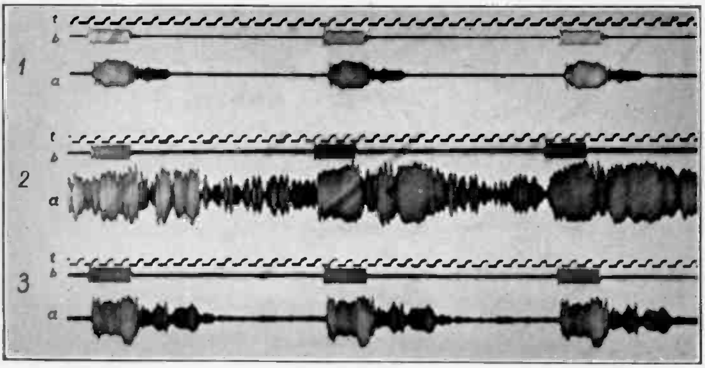

Fig. 20—Oscillograms of Tone Tests. Curve 1: in the studio of the broadcast transmitter in Munich. Curve 2: in an entrance hall of the Institute of Technology in Munich. Curve 3: the same as in curve 2, but the floor having been covered with a sound absorbing material.

the ear tone groups cannot be distinguished at all. Conditions were still worse when the frequency of the tone used coincided with that of a free oscillation of the hall. If now the acoustical conditions were examined by a shock test, it was found that the path of the sound rays was approximately that shown in the lower part of Fig. 21, the loudspeaker being at the point of the shaded circle. As shown by this drawing the sound is first reflected at the arched ceiling, concentrated near the floor and then reflected by it, then reflected again at the ceiling and so on. This goes on for many seonds owing to the absorption by the ceiling as well as that by the floor being very weak. Now it was to be expected that this almost infinite series could be cut off after the first term if the sound could be absorbed at its first arrival

from the ceiling. We did this by covering the floor with *molton,* which is a thick fabric. The result will be seen from curve 3*a* in Fig. 20. This shows that by simply covering the floor the former extremely bad acoustic properties of the hall were improved to such a degree that they were not much inferior to those of the broadcast studio represented by curve 1*a*. Interesting in this connection is the fact that by covering the floor the bad acoustic in-

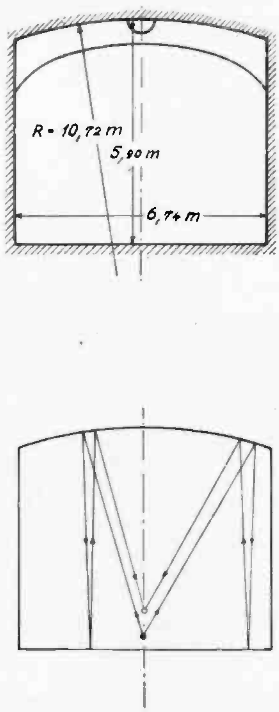

Fig. 21—Elevation of the Hall (to which curves 2 and 3 of Fig. 20 refer) and Path of Sound Rays.

fluence of the ceiling has been eliminated, aside from the first reflection thereon, which however is relatively harmless, since it follows the direct sound at a very short interval. Still more interesting is the following observation made in the course of these experiments. When the source of sound is located at the side of the hall, the sound rays by the first reflection from the arched ceiling are concentrated on a relatively small part of the floor. If, then, this part only is covered by a sound absorbing material, practically the same result is obtained as if the whole floor had

been covered. In our experiments a piece of *molton* four square meters in size was sufficient. It was very interesting to hear the sound of the interrupted loudspeaker in the hall suddenly change when this piece of *molton* was alternately put down and taken away. There are many instances such as lecture rooms or churches, where the speaker always stands at the same place. From the experience just mentioned it is to be concluded that in such cases it might be possible to improve the acoustic properties of the room by very simple means, of course for only one definite position of the speaker.

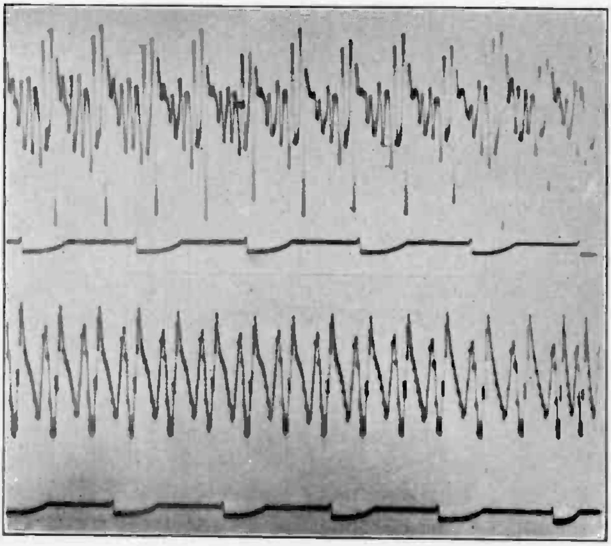

Fig. 22—Time Curves of the Vowels *e* and *a*.

As further evidence of how far the experimental methods furnished by radiotelegraphy came into use in acoustics I want to quote the experiments recently made with oscillations of ultrasonic frequency of the order of some 100,000 per second. How closely modern acoustic methods are coupled with radiotelegraphy can be best proven from the fact that it is now common practice to publish papers on acoustics in journals of radiotelegraphy such as the PROCEEDINGS of the Institute.

It is also but natural that physiological acoustics, which of course is closely related to physical acoustics, enjoys the experi-

mental means afforded by radiotelegraphy.[19] Let me show just one instance. In Fig. 22 there are reproduced the time curves of the vowels *a* (as in "are") and *e* (as in "Ellen") which were taken in my laboratory with a Reiss microphone, a resistance-capacity coupled multi-stage amplifier, and a Siemens oscillograph. The progress obtained by these modern experimental means cannot be better demonstrated than by comparing those curves showing the finest details of sound with the corresponding curves as formerly taken with the so-called manometric boxes and flames.

It is but recently that medical science is beginning to make use of the apparatus developed in radiotelegraphy and in modern acoustics. To illustrate this I want to show you, from a paper by H. Trendelenburg,[20] two records of heart sounds taken with a

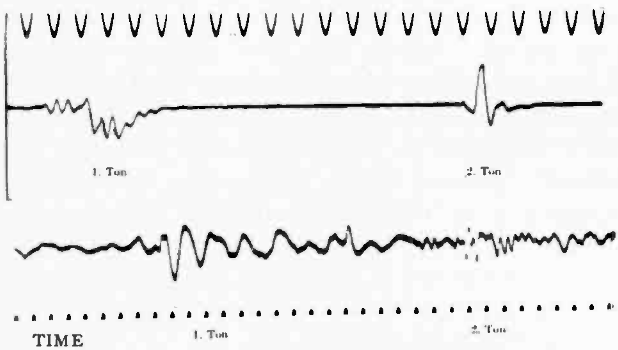

Fig. 23—Time Curves of Heart Sounds.

similar arrangement to that above mentioned except that the microphone used was the excellent high-frequency condenser microphone constructed by H. Riegger of the Siemens and Halske Co. The second curve of Fig. 23 shows the time curve of the heart sound of a healthy man of 31 years while the third curve of the same figure represents the corresponding record obtained with a woman of 70 years of age suffering from a serious heart disease. There is certainly no knowledge of medicine needed to realize that such curves afford a much more reliable basis for diagnosis than mere listening to the sound as was hitherto general practice.

[19] F. Trendelenburg, *Jahrb. d. Draht Tel.*, **28**, 54, 84, 1926.

[20] F. Trendelenburg, *Wissenschaftl. Veröffentlichungen aus dem Siemens-Konzern*, **6**, 184, 1928.

It would be an attractive proposition to discuss now one science which recently came into close contact with radiotelegraphy—the physics of the atmosphere. There can be no doubt that the recent investigations into the propagation of radio waves are of extreme interest for radiotelegraphy itself. But with regard to the physics of the atmosphere it is hardly possible to draw therefrom any conclusions which go beyond a rather rough estimation of the electron density in different heights. Similar is the case with the influence on the propagation of radio waves of solar activity as discussed in the well-known papers by Dr. L. W. Austin and G. W. Pickard. It seems to me that we are only at the beginning of an interesting development which, however, is encountering special difficulties since it lacks the main requirement of experiments, the modification of conditions at will. It would seem premature to go into any details today.

I have tried to illustrate by a few examples what science in the most general sense of the word owes to radiotelegraphy. The importance of a scientific discovery or of a technical invention may be judged from the practical results obtained, or from the impetus it has given to the development of science and to the enlargement of general human knowledge. From either point of view it seems to me that there is nothing to be compared with radiotelegraphy, and this country and the members of this Institute may be proud of the original ideas they have produced and of what they have done for the scientific and practical development of this art.

Proceedings of the Institute of Radio Engineers
Volume 17, Number 1 *January, 1929*

AN AUXILIARY FREQUENCY CONTROL FOR R. F. OSCILLATORS*

By
G. F. Lampkin

Summary—*A method of varying the frequency of an oscillator in small known amounts is described. The control operates on the normally fixed element in the oscillating circuit. The vernier calibration is readily made and maintained.*

DETERMINATION of the overall characteristics of a receiving set requires that some sort of a local modulated oscillator be used to simulate a transmitting station. Determination of the particular characteristic of selectivity necessitates that the oscillator frequency be capable of variation in small steps about any given frequency. To obtain transmission-frequency characteristics of single circuits, band-pass filters, coupled circuits, and so on, an auxiliary control of the

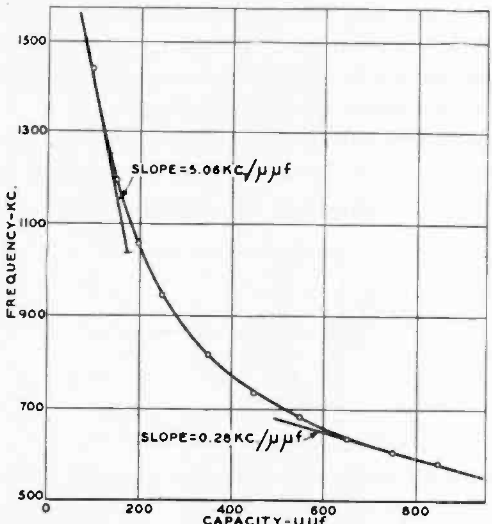

Fig. 1—Frequency-Capacity Relation for Oscillating Circuit.

same sort is needed. It is the purpose of this paper to describe a method for varying the frequency of an oscillator in small, continuous, and known amounts about any frequency in the oscillator range.

* Dewey decimal classification: R351. Original manuscript received by the Institute, September 22, 1928.

The usual oscillator employs a variable condenser as a means of covering the frequency range. A small semi-circular plate condenser can be used in parallel as a vernier frequency control. The calibrations of frequency change vs. dial setting will be straight lines for any given setting of the main control. However, the value of cycle change per auxiliary-dial division will vary widely over the oscillator range. This is evident from the measured frequency-capacity relation, Fig. 1, for a typical oscillator.

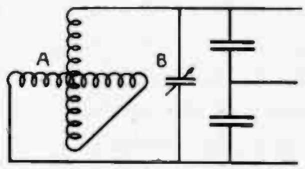

Fig. 2a—Oscillator Circuit with Capacitive Auxiliary Frequency Control.

At 600 kc a small auxiliary condenser would produce a change of 281 cycles per $\mu\mu$f. At 1400 kc the change would be 18 times as great, or 5060 cycles per $\mu\mu$f. This extreme variation in the calibration constant is not only inconvenient in itself, but it lowers the precision of control at higher frequencies.

A remedy can be had in a circuit such as Fig. 2a, or vice versa, 2b. Element A in each circuit represents the main tuning control and element B the auxiliary frequency control. The auxiliary

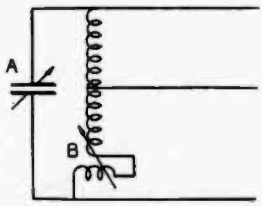

Fig. 2b—Oscillator Circuit with Inductive Auxiliary Frequency Control.

operates on the fixed element of the oscillating circuit. The change in total capacity, or total inductance, due to the auxiliary is then nearly constant over the oscillator frequency range.

Fig. 3 shows the calibration curves that were obtained on an oscillator of the type in Fig. 2a. A variable inductor of 38 to 370 μh was the main tuning control. The double condenser capacity was 320–320 $\mu\mu$f; the maximum capacity of the auxiliary was 8.6 $\mu\mu$f. The calibrations obtained are straight lines; the ratio of the

slopes at 1400 kc and 625 kc is approximately 2. These auxiliary calibrations were determined by picking up and heterodyning in a detector a small fraction of the oscillator output. The frequency of the beat was measured by sound comparison with a calibrated audio oscillator.

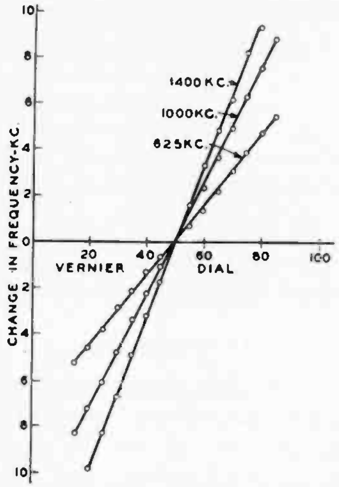

Fig. 3—Calibration of Auxiliary Frequency Control. Slope for 1400 kc = 326 cycles/division; 1000 kc = 249 cycles/division; 625 kc = 154 cycles/division.

Since the change-in-frequency calibrations are straight lines, a value of cycles change per auxiliary-dial division can be determined for each carrier frequency, and the resulting curve plotted. This curve for the particular oscillator is given in Fig. 4. Thus at

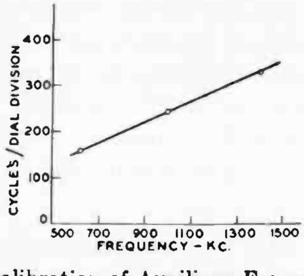

Fig. 4—Calibration of Auxiliary Frequency Control.

any given oscillator frequency the change in frequency due to the auxiliary is known. If the auxiliary control were made a small variometer, and the main control a straight-line-frequency condenser, then the calibrations of both the main and auxiliary frequency controls would be linear.

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A METHOD OF TREATING RESISTANCE STABILIZED RADIO-FREQUENCY AMPLIFYING CIRCUITS*

By

B. L. Snavely and J. S. Webb
(Department of Physics, Lehigh University, Bethlehem, Pennsylvania)

Summary.—*An equation is developed showing the relation between the circuit constants and the critical resistance in a resistance stabilized amplifier having a tuned grid circuit and a pure inductance plate load. In the derivation of this equation it has been found necessary to assume the grid to filament capacity to be zero. Equations are given which may serve as a basis for approximation formulas which will take this capacity into account.*

The experimental results suggest a convenient method of measuring very small capacities, and demonstrate the possibility of controlling regeneration, in this type of circuit, by means of a small condenser between the grid and filament.

Introduction

RECENTLY there has been considerable use of tuned radio-frequency amplifying circuits employing a resistance in the grid circuit for the purpose of preventing oscillation. The type of circuit referred to is shown in Fig. 1. The resistance R has been called the suppressing resistance or the oscillation suppressor, and the method has been termed resistance stabilization or resistance neutralization.

Steady oscillation cannot occur if the value of R exceeds the value of the negative input resistance of the tube. The value of R for which oscillations are just maintained when once started is here termed the *critical value.*

Since the input capacity of the tube is generally not negligible in comparison with C, any increase of R beyond the critical value causes an effective increase in the resistance of the tuned circuit LC and hence results in a decrease in the sharpness of tuning and efficiency of the amplifier. It therefore becomes desirable to have some means of calculating the critical value of R, which we shall call R_c.

Circuit Characteristics

In order that a general expression for R_c might be arrived at, it has been found necessary to make the following assumptions regarding the circuit:

* Dewey decimal classification: R132. Original manuscript received by the Institute, October 6, 1928.

(a) No current flows between the grid and the filament in the tube.

(b) The plate circuit load is a pure inductance.

(c) The plate to filament capacity is negligible.

(d) The grid to filament capacity is zero.

Assumption (a) is generally fulfilled in most amplifiers.

Assumptions (b), (c), and (d) necessarily limit the direct practical application of the results. Ballantine has shown that the input characteristics of a vacuum tube having an inductance load are not appreciably affected by the resistance of the load provided the resistance does not exceed several ohms.[1] Hence our results may be extended with fair accuracy to the case in which the plate load consists of a pure inductance in series with a pure resistance.

The grid to filament capacity influences the value of the critical resistance quite markedly; hence the results here obtained must be corrected for this capacity.

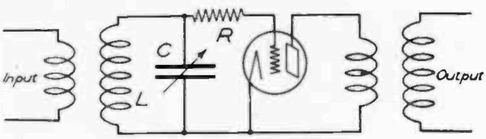

Fig. 1

On the basis of the above assumptions, the circuit analytically equivalent to that of Fig. 1 is shown in Fig. 2. In the latter figure we have:

R_p = plate impedance of the tube.

C_{pg} = grid to plate capacity in the tube.

e_p = a fictitious emf set up within the tube due to the instantaneous grid potential e_g.

Determination of the Critical Resistance

The currents in the circuit will be governed by the following equations:

$$L_1\frac{d}{dt}i_1+R_1i_1+\frac{1}{C_1}\int(i_1-i_2)dt=0 \tag{1}$$

$$\frac{1}{C_1}\int(i_2-i_1)dt+Ri_2+\frac{1}{C_{pg}}\int i_2dt+R_p(i_2-i_3)=e_p \tag{2}$$

[1] *Phys. Rev.*, 15, 409, 1920.

$$R_p(i_3-i_2)+L_p\frac{d}{dt}i_3=-e_p \tag{3}$$

$$-e_g=Ri_2+\frac{1}{C_1}\int(i_2-i_1)dt \tag{4}$$

$$e_p=\mu e_g \tag{5}$$

These, upon differentiation and elimination of e_g and e_p yield:

$$\left(L_1\frac{d^2}{dt^2}+R_1\frac{d}{dt}+\frac{1}{C_1}\right)i_1-\frac{1}{C_1}i_2=0 \tag{6}$$

$$-\left(\frac{1+\mu}{C_1}\right)i_1+\left[R(1+\mu)\frac{d}{dt}+R_p\frac{d}{dt}\right.$$
$$\left.+\frac{1}{C_{pg}}+\frac{1+\mu}{C_1}\right]i_2-R_p\frac{d}{dt}i_3=0 \tag{7}$$

$$-\frac{\mu}{C_1}i_1+\left(R_p\frac{d}{dt}+\mu R\frac{d}{dt}+\frac{\mu}{C_1}\right)i_2$$
$$-\left(L_p\frac{d^2}{dt^2}+R_p\frac{d}{dt}\right)i_3=0 \tag{8}$$

From the above simultaneous differential equations we obtain by differentiation and elimination the equation which each of the currents must satisfy:

$$\begin{aligned}
&\{L_1L_p[(1+\mu)R+R_p]\}D^4i\\
&+\left\{L_1RR_p+L_pR_1[(1+\mu)R+R_p]+L_1L_p\left(\frac{1}{C_{pg}}+\frac{1+\mu}{C_1}\right)\right\}D^3i\\
&+\left\{L_1R_p\left(\frac{1}{C_{pg}}+\frac{1}{C_1}\right)+L_pR_1\left(\frac{1}{C_{pg}}+\frac{1+\mu}{C_1}\right)\right.\\
&\left.+L_p\frac{1}{C_1}[(1+\mu)R+R_p]+R_1RR_p\right\}D^2i\\
&+\left\{R_1R_p\left(\frac{1}{C_{pg}}+\frac{1}{C_1}\right)+R_pR\frac{1}{C_1}+L_p\frac{1}{C_1}\frac{1}{C_{pg}}\right\}Di\\
&+R_p\frac{1}{C_1}\frac{1}{C_{pg}}=0.
\end{aligned} \tag{9}$$

Suppose, for convenience, that this equation is written as:

$$(D^4+aD^3+bD^2+cD+d)i=0 \tag{10}$$

The general solution will be of the form:

$$i=Ae^{\alpha_1 t}\sin(\omega_1 t+\theta_1)+Be^{\alpha_2 t}\sin(\omega_2 t+\theta_2)$$

where A, B, θ_1, and θ_2 are arbitrary constants and α_1, α_2, ω_1, ω_2 are such that $\alpha_1+j\omega_1$; $\alpha_1-j\omega_1$; $\alpha_2+j\omega_2$; $\alpha_2-j\omega_2$ are the roots of (10) regarded as an equation in powers of D.

The following relations will hold between the roots and the coefficients of (10):

$$\left.\begin{aligned} 2(\alpha_1+\alpha_2)&=-a\\ 4\alpha_1\alpha_2+\Omega_1^2+\Omega_2^2&=b\\ 2\alpha_2\Omega_1^2+2\alpha_1\Omega_2^2&=-c\\ \Omega_1^2\Omega_2^2&=d \end{aligned}\right\} \tag{11}$$

where

$$\Omega_1^2=\alpha_1^2+\omega_1^2$$

and

$$\Omega_2^2=\alpha_2^2+\omega_2^2$$

It may be easily shown that if either α_1 or α_2 is zero, the following relation must hold among the coefficients:

$$c^2+a^2d-abc=0 \tag{12}$$

Conversely, if (12) is true then either α_1 or α_2 must be zero, for if we substitute for a, b, c, and d in (12), the values given by (11), and reduce, we obtain:

$$c^2+a^2d-abc=-\alpha_1\alpha_2[4(\alpha_2\Omega_1^2+\alpha_1\Omega_2^2)(\alpha_1+\alpha_2)+(\Omega_1^2-\Omega_2^2)^2] \tag{13}$$

Now it is seen by reference to (9) and (10) that a and c are always positive. Hence, $4(\alpha_2\Omega_1^2+\alpha_1\Omega_2^2)(\alpha_1+\alpha_2)$, which is equal to $a\,c$, must be positive and the coefficient of $\alpha_1\alpha_2$ in (13) is under no circumstances zero. Hence if c^2+a^2d-abc vanishes, either α_1 or α_2 must be zero. Suppose α_1 is zero.

From the first of the equations (11) it is seen that $\alpha_1+\alpha_2$ must be negative. Under these circumstances, therefore, oscillations of frequency ω_1 when once started will be maintained with unchanged amplitude. Oscillations of frequency ω_2, which occur

when the circuit is given an electrical jar, will die out because α_2 is negative.

Therefore (12) regarded as an equation in R gives the value of R for which oscillations will just be maintained. This is the critical value, R_c, of the stabilizing resistance.

If in (12) we substitute for a, b, c, and d their values in terms of the circuit constants and clear of fractions, we obtain by placing $R=R_c$:

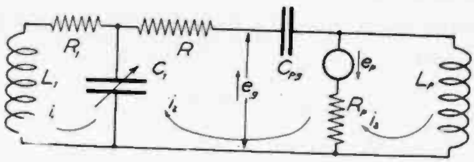

Fig. 2

$$
\begin{aligned}
&L_1L_p[(1+\mu)R_c+R_p]\left\{R_1R_p\left(\frac{1}{C_{pg}}+\frac{1}{C_1}\right)+R_pR_c\frac{1}{C_1}+L_p\frac{1}{C_1}\,\frac{1}{C_{pg}}\right\}^2\\
&\quad+\left\{L_1R_cR_p+L_pR_1[(1+\mu)R_c+R_p]\right.\\
&\qquad\qquad\left.+L_1L_p\left(\frac{1}{C_{pg}}+\frac{1+\mu}{C_1}\right)\right\}^2R_p\frac{1}{C_1}\,\frac{1}{C_{pg}}\\
&\quad-\left\{L_1R_cR_p+L_pR_1[(1+\mu)R_c+R_p]+L_1L_p\left(\frac{1}{C_{pg}}+\frac{1+\mu}{C_1}\right)\right\}\\
&\quad\left\{L_1R_p\left(\frac{1}{C_{pg}}+\frac{1}{C_1}\right)+L_pR_1\left(\frac{1}{C_{pg}}+\frac{1+\mu}{C_1}\right)\right.\\
&\qquad\qquad\left.+L_p\frac{1}{C_1}[(1+\mu)R_c+R_p]+R_1R_cR_p\right\}\\
&\quad\left\{R_1R_p\left(\frac{1}{C_{pg}}+\frac{1}{C_1}\right)+R_pR_c\frac{1}{C_1}+L_p\frac{1}{C_1}\,\frac{1}{C_{pg}}\right\}=0 \qquad (14)
\end{aligned}
$$

In case R_1 is negligible, (14) may be reduced to:

$$
\begin{aligned}
&R_p\left\{L_1R_p^2+L_p^2\frac{(1+\mu)^2}{C_1}\right\}R_c^2\\
&\quad+L_p\left\{L_1R_p^2\left(\frac{1}{C_{pg}}+\frac{1+\mu}{C_1}\right)-L_1R_p^2\frac{\mu}{C_{pg}}+L_p^2\frac{(1+\mu)^2}{C_1C_{pg}}\right.
\end{aligned}
$$

$$+L_pR_p^2\frac{1+\mu}{C_1}\Big\}R_c$$

$$+R_pL_p^2\frac{1}{C_{pg}}\left\{L_p\frac{1+\mu}{C_1}-L_1\mu\left(\frac{1}{C_{pg}}+\frac{1+\mu}{C_1}\right)\right\}=0 \qquad (15)$$

The Critical Frequency

The critical angular velocity, ω_c, is the value of ω_1, say, when $\alpha_1=0$.

When $\alpha_1=0$, we see from equations (11) that;

$$2\alpha_2=-a$$

$$2\alpha_2\omega_c^2=-c$$

Therefore,

$$\omega_c^2=\frac{c}{a}$$

Substituting for c and a, and remembering that R is adjusted to the critical value R_c:

$$\omega_c^2=\frac{1}{L_1C_1}\left[\frac{R_pR_c+L_p\dfrac{1}{C_{pg}}}{R_pR_c+L_p\left(\dfrac{1}{C_{pg}}+\dfrac{1+\mu}{C_1}\right)}\right] \qquad (16)$$

General Equations for R_c When the Plate Load is of Any Type

Considering merely the input characteristics of the vacuum tube without detailed reference to the plate circuit, we may consider the grid circuit of the tube to be of the form shown in

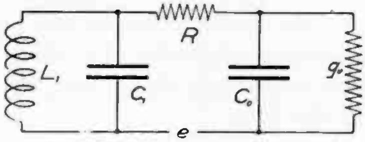

Fig. 3

Fig. 3. Here g_o is the input conductance of the tube and C_o is the input capacity. The circuit LC is assumed to be of negligible resistance.

The complex impedance which a current flowing under the action of an emf, e, would encounter is:

$$z = R + \frac{g_o}{\omega^2 C_o{}^2 + g_o{}^2} - \frac{\omega C_o j}{\omega^2 C_o{}^2 + g_o{}^2} + \frac{\omega L_1 j}{1 - \omega^2 L_1 C_1}.$$

If any oscillations started in the circuit are just maintained after the removal of e, both the real and imaginary parts of z must be zero. Hence we must have:

$$R = R_c = \frac{-g_o}{\omega_c{}^2 C_o{}^2 + g_o{}^2} \tag{17}$$

and

$$\frac{\omega_c L_1 j}{1 - \omega_c{}^2 L_1 C_1} = \frac{\omega_c C_o j}{\omega_c{}^2 C_o{}^2 + g_o{}^2}$$

or

$$\omega_c{}^2 = \frac{C_o - L_1 g_o{}^2}{L_1 C_o (C_o + C_1)} \tag{18}$$

Verification of Results

The circuit shown in Fig. 4 was used in checking (15). Oscillation was detected by heterodyning with the autodyne circuit A, which was very loosely coupled to the plate inductance, L_p. It was found that the sudden change in plate current caused by the commencement or cessation of oscillations was a more sensitive criterion of oscillation than was given by the autodyne circuit.

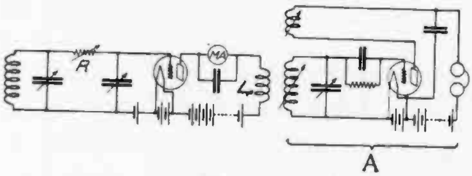

Fig. 4

The grid to filament capacity was made variable by means of a small condenser connected between the grid and filament. The total grid to filament capacity, C_{gf}, then, was the sum of the capacities of this condenser, the wiring, the socket, and the internal capacity of the tube.

The data for the curve shown in Fig. 5 was obtained by setting C_{gf} at some known value and then increasing R until oscillations ceased. These values of R_c were then plotted against the corresponding values of C_{gf} and the curve so obtained was extrapolated to give R_c when $C_{gf} = 0$. The values of the critical resistance thus obtained were found to agree with the values calculated from (15).

If we solve for R_c and ω_c in (15) and (16) and place these values in (17) and (18), we can solve these latter equations simultaneously for C_o and g_o. C_o and g_o as calculated by this method agreed exactly with the values calculated by means of Ballantine's formulas.[2]

Discussion

Fig. 5 shows the great change of R_c for a small change in grid to filament capacity when this capacity is small. The results given here may be made to serve as a basis for approximation formulas which will take account of the grid to filament capacity. Equations (17) and (18) may be made the basis of such formulas.

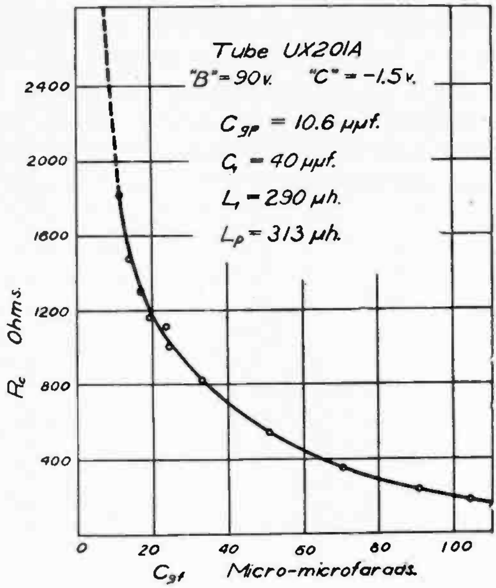

Fig. 5

If in equation (15), $R_c=0$, the critical condition is expressed by:

$$L_p\frac{1+\mu}{C_1}-L_1\mu\left(\frac{1}{C_{pg}}+\frac{1+\mu}{C_1}\right)=0. \tag{19}$$

In case C_1 is zero we have an Hartley oscillator circuit with no mutual inductance between the grid and plate circuits. The above equation then becomes:

[2] *Phys. Rev.*, 15, 409, 1920.

$$L_p - \mu L_1 = 0. \tag{20}$$

This critical relation is in agreement with the observations of several writers.

The critical resistance could always be located to within a fraction of one per cent of its value. This fact and the great steepness of the curve in Fig. 5 suggest a method of measuring very small capacities. The unknown capacity would be placed between the grid and the filament of the vacuum tube. The change of the critical resistance thus produced by the added capacity would be a measure of this capacity. Such an application would, however, require consideration of the stability of operation of the tube.

Fig. 5 demonstrates the possibility of controlling regeneration by means of a condenser between the grid and the filament. If R remains fixed, we can, by varying C_{gf}, change the critical resistance R_c and cause it to approach R. When the circuit is not oscillating R must be greater than R_c. As R_c approaches R the regeneration will increase.

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THE PIEZO-ELECTRIC CRYSTAL OSCILLATOR*

By
J. Warren Wright
(Bureau of Engineering, Navy Department, Washington, D. C.)†

Summary—*The zero-angle quartz crystal, having electrodes in direct contact with its surface, is used to control the output of a typical oscillating crystal circuit.*

The crystal is first considered as a simple mechanical oscillator, and the required plate circuit adjustment for sustained vibrations of the crystal obtained by Miler's method on the basis of an assumed electrically equivalent crystal circuit.

The electrical equivalent of the crystal is then considered as the grid circuit of an oscillating vacuum-tube circuit and the equations for the frequency and condition for oscillation derived.

The effects of the tube and circuit upon the frequency of a crystal-controlled oscillator are then shown.

THERE are several very good articles[1] on the piezo-electric crystal resonator in the current literature, but little information has been made available, for general use, concerning the operation and theory of the piezo-electric crystal oscillator.[1,2] In this article an attempt is made to discuss the piezo-electric crystal oscillator from a theoretical and mathematical viewpoint.

We wish to examine just what takes place when a crystal is placed in a typical oscillating crystal circuit such as is shown in Fig. 1, and the circuit is adjusted so that sustained crystal-controlled oscillations result.

Let us first consider the crystal merely as an elastic substance placed between the plates *a* and *b*, Fig. 2. Suppose that pressure is applied to plate *a* (plate *b* assumed fixed), causing a slight deformation of the crystal, and then suddenly removed. Owing to its elastic properties, the crystal will tend to spring back to its former shape, but owing to its inertia the process will be carried too far, and thus a system of damped vibrations depending on the dimensions and physical properties of the quartz will be set up.

* Dewey decimal classification: R214. Original manuscript received by the Institute, April 30, 1928; revised manuscript received October 3, 1928. Published by permission of the Navy Department.

† Formerly of Naval Research Laboratory.

[1] For example, D. W. Dye, *Proc.* Phys. Soc. of London, **38**, part 5, 399, 1926; and W. G. Cady, Proc. I.R.E., **10**, 83; April, 1922.

[2] G. W. Pierce, *Proc.* Amer. Acad. of Arts and Sciences, **59**, 82, 1923.

We will confine our attention to vibrations along the X axis[3] of the crystal, Fig. 2, and assume that the crystal acts like a simple mechanical system when set in vibration. Then if we let x be the displacement of the face of the crystal in contact with plate a along the X crystal axis, above or below the position assumed by this face when the crystal is not oscillating, we can write

$$(\alpha D^2+\beta D+\gamma)x=F=F_0 \cos \omega t \tag{1}$$

where $D=\dfrac{d}{dt}\cdot$ F is the applied force and it will be assumed that it affects only the damping term directly. Therefore such substitutions as are made in (2) and (5) hold only at or very close to the resonant frequency, where F and Dx are nearly in phase. α, β, and γ are the coefficients of inertia, damping, and restoration, respectively. They are constants of the quartz and its mounting.

It will be assumed, in all that follows, that we are dealing with vibrations along the X crystal axis and that the elastic limit of the quartz is never exceeded.

Equation (1) can take three forms, that is, in Equation (1), F can be (1) positive, (2) zero, or (3) negative. Cases (2) and(3) do not interest us here as they do not give sustained oscillations, and in solving Equation (1) we are only interested in the cases where oscillations are possible, and hence will omit the others.

Case (1a). *F* positive and just equal to the damping term. Equation (1) becomes

$$(\alpha D^2+\gamma)x=0 \tag{2}$$

The solution of (2) can be written

$$x=A \sin (\eta t+\rho) \tag{3}$$

where A is the amplitude of vibration, ρ is a constant, and η is the angular velocity.

An examination of Equation (3) shows that the period of vibration of the crystal, under these conditions, is given by

$$T=\frac{2\pi}{\eta} \tag{4}$$

[3] A. Crossley, Proc. I.R.E., 15, 9; January, 1927.

where T is the time in seconds for one complete mechanical oscillation.

Now $T=\dfrac{1}{f}$ where f is the frequency of vibration, hence $f=\dfrac{\eta}{2\pi}$.

Case (1b). F is positive and greater than the damping term. Under these conditions Equation (1) becomes

$$(\alpha D^2 - K\beta D + \gamma)x = 0 \tag{5}$$

where K is a factor depending on the magnitude of F and βDx.

Equation (5) states (under the assumption that F and Dx are in phase) that more energy is being supplied to the system than required to overcome its losses. The solution of (5), if we let $\delta_1 = \dfrac{K\beta}{\alpha}$ and $\eta^2 = \dfrac{\gamma}{\alpha}$ can be written as

$$x = A_1 e^{1/2\delta_1 t} \sin\left(\sqrt{\eta^3 - \tfrac{1}{4}\delta_1{}^2}\, t + \epsilon_1\right) \tag{6}$$

where A_1 is the original amplitude of vibration and ϵ_1 is a constant.

The period of vibration, in this case, can be shown to be

$$T_1 = \frac{2\pi}{\sqrt{\eta^2 - \frac{1}{4}\delta_1{}^2}} \tag{7}$$

and if this is expanded, by the use of Taylor's Theorem, we have

$$T_1 = \frac{2\pi}{\eta} + \frac{\pi\delta_1{}^2}{4\eta^3} + \text{-----} \tag{8}$$

An inspection of (8) shows that the period of vibration has increased owing to the fact that more energy is being supplied to the system than is needed to overcome the losses. The extra energy over and above that used to supply the losses, goes to build up larger oscillations. An inspection of (6) shows that, under these conditions, the oscillations would continue to increase in amplitude indefinitely. We can avoid this absurdity, in our case, by remembering that the energy must be supplied by the tube (see Fig. 1) and that, as the energy supplied is electrical, the characteristic curve of the tube employed serves to limit the increase in amplitude of the mechanical oscillations. Hence once the amplitude of vibration A_1 of (6) reaches this limit, there is

no further increase in amplitude nor change in the period of the oscillations.

Experiments[4] have shown that when pressure is applied to a piece of piezo-electric quartz (zero-angle[3] cut considered here) a piezo-electric charge is developed on plates *a* and *b* which are in intimate contact with the quartz crystal. This is true whether the pressure is applied along the *X* or the *Y* axis. See Fig. 2.

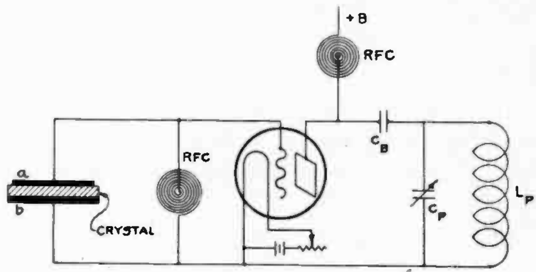

Fig. 1

It follows at once that if a crystal is caused to vibrate, these vibrations produce changes in stress in the crystal itself, and that a component of piezo-electric charge in phase with this stress will be developed on the electrodes *a* and *b*. The converse, that an oscillating charge will produce a mechanical vibration in a piezo-electric quartz crystal, is also true.

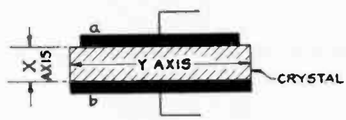

Fig. 2

Such a charge is due to the piezo-electric properties of the quartz crystal and it gives rise to an emf which can be expressed as

$$e = \frac{K'Q}{C} e^{\pm \tau t} \sin \omega t \tag{9}$$

where $e^{\pm \tau t}$ is a damping term which becomes unity if τ is zero, Q is the piezo-electric charge, C is associated capacity, K' is a constant, and $\omega = 2\pi f$ where f is the frequency of vibration of the quartz crystal.

[4] This effect was first noted by the Curies. A recent detailed study of it was made by L. H. Dawson, *Phys. Rev.*, 29, 532, 1927.

It is well to note by (9) that, for a given charge Q, the emf developed by the crystal is inversely proportional to the capacity associated with it. This capacity is the sum of the capacities of the crystal and holder, the capacity of the leads and the tube capacity. This capacity might be considered as a part of C', Fig. 3.

The frequency f is that of the mechanical vibration of the quartz, and is a function of the dimensions of the crystal and of the axis used. It is also a function of the input capacity of the vacuum tube used and the amplitude of mechanical vibration. In a properly ground zero-angle crystal there are three natural frequencies[3,5]; (a) that corresponding to the mechanical vibration of the crystal along the X axis, (b) that corresponding to the mechanical vibration along the Y axis, and (c) the so-called *coupling frequency.*

It would seem, then, that the frequency of a crystal oscillator might shift from one to another of the natural frequencies of the crystal. This is not the case, however, with a properly ground crystal, since the natural frequencies are separated far enough from each other so that tuning the plate circuit, Fig. 1, to produce oscillations at one frequency results in circuit conditions which are, in general, unfavorable to the production of the other two frequencies.

In order for the circuit of Fig. 1 to generate sustained crystal-controlled oscillations, assuming the crystal to impress an emf as given by (9) on the grid of the vacuum tube, the losses in the crystal must be supplied by the tube circuit. When this condition is satisfied the crystal continues to vibrate with constant amplitude, and owing to its piezo-electric properties it excites the grid of the tube with an undamped emf. This means that the damping term of (9) becomes unity for this condition.

Now in the case of the piezo-electric quartz crystal we have a mechanical vibration producing an electrical oscillation, and in general an electrical oscillation can be represented by an equation of the form

$$\left(LD^2+RD+\frac{1}{C}\right)q=e \tag{10}$$

where $D=\dfrac{d}{dt}$, l is the emf, q is the charge, while L, R, and C are the inductance, resistance, and capacity, respectively.

[5] A. Hund, PROC. I.R.E., 14, 447; August, 1926.

The similarity between (1) and (10) is marked and it has been shown[6] that an equivalent electrical system can be substituted for the mechanical one for the purpose of studying the frequency and conditions for oscillations in a circuit such as Fig. 1. However, it must not be assumed that in actual practice a crystal can be replaced by an equivalent electrical circuit and still afford the stability of frequency which is a feature of the crystal-controlled oscillator.

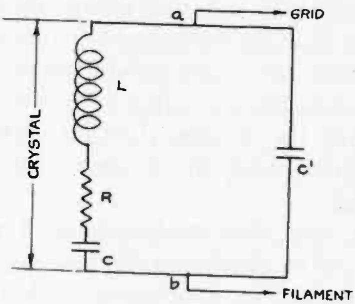

Fig. 3

Furthermore, it has been shown that the series chain of such an equivalent electrical system (Fig. 3) would have constants[6,7] given by

$$L = a\alpha \qquad R = b\beta \qquad C = c\gamma \tag{11}$$

where α, β, and γ are as defined in (1), while L, R, and C are the inductance, resistance, and capacity, respectively, and a, b, and c are constants. C' is the capacity of the quartz condenser.[7]

Such an equivalent electrical system[1] is shown in Fig. 3 where it is assumed that the electrodes rest directly on the crystal.

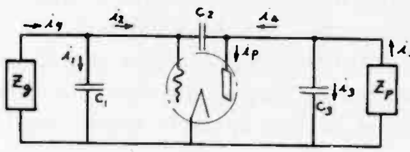

Fig. 4

Since we can replace a given crystal operating along a given axis by a fixed equivalent electrical circuit, our problem is to show the necessary conditions of adjustment of the plate circuit,

[6] Butterworth, *Proc.* Phys. Soc. of London, 271, 410, 1915.
[7] Van Dyke, K. S., Proc. I.R.E., 16, 742; June, 1928.

Fig. 1, so that the resistance term of our equivalent electrical circuit is neutralized. This will also be the condition for the damping term of (1) to vanish, and hence if we can find such an adjustment sustained crystal-controlled oscillations are possible.

Miller[8] has shown that a vacuum tube will supply energy to the input circuit provided that the load in the plate circuit is inductive. Hence the condition for the damping term of (1) to vanish can be satisfied by tuning the plate circuit (Fig. 1), so that the resonant frequency of L_pC_p is greater than the crystal frequency.

Let us now attack the problem using Miller's[8] method, and determine the required plate circuit tuning so that the tube circuit will neutralize the resistance of the external input circuit.

We shall refer to Fig. 4 and assume that the vacuum tube has a linear characteristic, and that the grid is held at such a potential with respect to the filament that it does not draw current. In this figure Z_g represents the input impedance, Z_p represents the load in the plate circuit, and C_1, C_2, and C_3 are the inter-electrode capacities.

From an inspection of Fig. 4 and using Kirchoff's laws we can write the following equations

$$i_g = i_1 + i_2 \tag{12}$$

$$i = i_2 + i_4 \tag{13}$$

$$i_4 = i_5 - i_3 \tag{14}$$

$$i_1 = \mathbf{e}_g j\omega C_1 \tag{15}$$

$$i^5 Z_p + \frac{i_3}{j\omega C_3} = 0 \tag{16}$$

$$\frac{i_3}{j\omega C_3} + \frac{i_2}{j\omega C_2} - \frac{i_1}{j\omega C_1} = 0 \tag{17}$$

and from vacuum-tube theory, assuming a linear characteristic,

$$\mu \mathbf{e}_g - i_p r_p - i_5 Z_p = 0, \tag{18}$$

where μ is the amplification constant, $\mathbf{e}_g$ is the instantaneous a.c. grid voltage, and r_p is the internal resistance (plate to filament) of the vacuum tube.

[8] John Miller, Bureau of Standards Scientific Paper No. 351, 1919.

Substituting (12), (13), (14), (15), (16), and (17) in (18) we have

$$\mathrm{e}_g\left(\mu+j\omega C_1 r_p+\frac{r_p}{Z_p}+\frac{r_p}{Z_p}\frac{C_1}{C_2}+j\omega C_3 r_p+\frac{j\omega C_1 C_3 r_p}{C_2}+\frac{C_1}{C_2}+1\right)$$

$$=i_g\left(r_p+\frac{r_p}{j\omega C_2 Z_p}+\frac{r_p C_3}{C_2}+\frac{1}{j\omega C_2}\right) \tag{19}$$

Equation (19) can be expressed in terms of an impedance if we remember that $Z_g=\dfrac{\mathrm{e}_g}{i_g}$, so we have

$$Z_g=\frac{r_p(C_2+C_3)+\dfrac{r_p}{j\omega Z_p}+\dfrac{1}{j\omega}}{\mu C_2+C_2+C_1+\dfrac{r_p}{Z_p}(C_1+C_2)+j\omega r_p(C_1C_2+C_1C_3+C_2C_3)} \tag{20}$$

and substituting $Z_p=R_p+jX_p$, equation (20) becomes

$$Z_g=\frac{R_p(C_2+C_3)+\dfrac{X_p}{\omega r_p}+j\left[X_p(C_2+C_3)-\dfrac{1}{\omega}-\dfrac{R_p}{\omega r_p}\right]}{\dfrac{R_p}{r_p}(\mu C_2+C_2+C_1)+(C_1+C_2)-\omega X_p(C_1C_2+C_2C_3+C_1C_3)+j\left[\dfrac{X_p}{r_p}(\mu C_2+C_2+C_1)+\omega R_p(C_1C_2+C_2C_3+C_1C_3)\right]}$$

This equation can be written in the form

$$Z_g=\frac{a+jb}{c+jd}=\frac{ac+bd}{c^2+d^2}+j\frac{bc-ad}{c^2+d^2}=R_g+jX_g \tag{22}$$

Here R_g is the resistance and X_g the reactance of the internal input impedance of the tube, and

$$\begin{aligned}
a&=R_p(C_2+C_3)+\frac{X_p}{\omega r_p}\\
b&=X_p(C_2+C_3)-\frac{1}{\omega}-\frac{R_p}{\omega r_p}\\
c&=\frac{R_p}{r_p}(\mu C_2+C_2+C_1)+(C_1+C_2)-\omega X_p(C_1C_2+C_2C_3+C_1C_3)\\
d&=\frac{X_p}{r_p}(\mu C_2+C_2+C_1)+\omega R_p(C_1C_2+C_2C_3+C_1C_3)
\end{aligned} \tag{23}$$

An examination of the resistance term of (22) shows that if X_p is positive, corresponding to an inductive load in the plate circuit, R_g becomes negative when

$$\frac{\mu X_p}{\omega r_p} > \frac{X_p^2}{r_p}[\mu(C_2+C_3)+C_2] + \frac{R_p^2}{r_p}[\mu(C_2+C_3)+C_2] + R_p C_2 \quad (24)$$

Hence if we make R_g negative by the use of the inequality (24) it means that the tube circuit is regenerating, and if we make R_g sufficiently negative so that the tube supplies the losses of the external input circuit, then oscillations are possible.

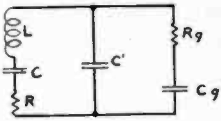

Fig. 5

This means that the tube circuit supplies the losses in the external input circuit and neutralizes the effect of the damping terms of (1) and (9). Hence, we have proved[9] that if the load in the plate circuit is made inductive, the resistance, and therefore (if we assume the use of the equivalent electrical circuit to be justified) the damping of the crystal can be overcome by the tube's supplying energy to the input, provided that the resistance is not too great.

An examination of the reactance term of (22) shows that X_g is a capacity reactance, and that the input impedance of the tube, under these conditions, can be represented by a resistance R_g in series with a capacity C_g. The values of this resistance and capacity are given by

$$R_g = \frac{ac+bd}{c^2+d^2} \quad (25)$$

and

$$C_g = \frac{c^2+d^2}{\omega(ad-bc)} \quad (26)$$

where a, b, c, and d are as given in (23).

The manner in which the electrical equivalent of the crystal is connected to the input of the vacuum tube is shown in Fig. 5. Here that portion of the circuit containing R_g and C_g in series

[9] This proof is in accord with Miller's, and is given here because it is felt that few engineers are familiar with his excellent paper.

represents the input impedance of the tube while the remainder represents the electrical equivalent of the crystal.

If we refer to Fig. 4 and to (25), and assume that R_g is negative, we note that the power supplied by the tube to the input circuit is given by

$$i_g^2 R_g = P_g \tag{27}$$

Now refer to Fig. 5 and assume[8] that a current i flows in that portion of the circuit representing the series chain of the crystal. If the reactance of C_g is large compared to the value of R_g, this current will divide between C' and C_g in proportion to their capacities. That part flowing through the series circuit containing R_g and C_g is the current referred to in Fig. 4 as i_g and can be expressed as

$$i_g = i\frac{C_g}{C'+C_g} \tag{28}$$

The power dissipated in the crystal is given by

$$P_C = i^2 R \tag{29}$$

If we substitute (28) in (27), and add the resultant power equation to (29) we have

$$P = i^2\left[R - \left(\frac{C_g}{C'+C_g}\right)^2 R_g\right] \tag{30}$$

where the negative sign indicates that the tube is supplying power to the input.

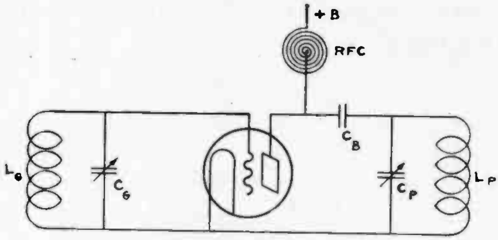

Fig. 6

When adjustments are made so that (30) becomes zero, sustained crystal-controlled oscillations are possible. It is well to note, however, that the frequency of these oscillations may differ if the tube is replaced by one having different interelectrode capacities, or if the plate circuit is retuned. These facts are

made clear by a study of Fig. 5 and (26). The change in the frequency of the crystal-controlled oscillations is very small, but may be important in the case of crystal-controlled oscillators which are to be used as frequency standards.

We have shown, assuming the use of the equivalent electrical circuit to be justified, that the plate circuit can be tuned so that the tube circuit will supply electrical energy to the input circuit, and, owing to the piezo-electric properties of the quartz crystal, maintain the mechanical vibrations of the crystal. These mechanical vibrations produce piezo-electric charges, and the tube is therefore excited by an undamped emf of the same frequency as that of the mechanical vibration of the crystal.

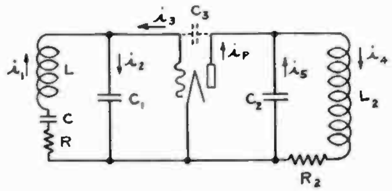

Fig. 7

We shall next consider the crystal-controlled oscillator as an oscillating vacuum-tube circuit, for it is well known that an inductance shunted by a capacity can be substituted for a crystal in an emergency, and that the circuit will then function with only slight changes in adjustments. This circuit is shown in Fig. 6 and is the so-called "Tuned-Grid Tuned-Plate Circuit."[10] It does not represent the electrical equivalent of the crystal[7] oscillator closely enough to be of interest here, so we shall replace the grid circuit of Fig. 6 by the electrical equivalent of the crystal as shown in Fig. 3. The resultant circuit is shown in Fig. 7.

Let us refer to Fig. 7 and assume, for simplicity, that the grid does not draw current, that the tube has a linear characteristic, and consider only small oscillations. In addition assume that the resistance is small compared to the reactance.

Now express the various currents of Fig. 7 in terms of the product of a voltage and an admittance.

Thus in the grid circuit

$$i_1 = e_g\left(g_1 - \frac{j}{X}\right) \tag{31}$$

[10] J. W. Wright, Proc. I.R.E., 16, 1113; August, 1928.

$$i_2 = \mathrm{e}_g j\omega C_1 \tag{32}$$

$$i_3 = (\mathrm{e}_p - \mathrm{e}_g) j\omega C_3 \tag{33}$$

$$i_1 = i_2 + i_3 \tag{34}$$

where $X = \left(\omega L - \dfrac{1}{\omega C}\right)$ and $g_1 = \dfrac{R}{X^2}$ e_g and e_p are the instantaneous alternating grid and plate voltages, respectively.

Substituting (31), (32), and (33) in (34) and solving for e_p,

$$\mathrm{e}_p = \frac{g_1 + j\left\{\omega(C_1 + C_3) - \dfrac{1}{X}\right\}}{j\omega C_3} \tag{35}$$

Similarly in the plate circuit

$$i_4 = \mathrm{e}_p \left(g_2 - \frac{j}{\omega L_2}\right) \tag{36}$$

$$i_5 = \mathrm{e}_p j\omega C_5 \tag{37}$$

$$i_p = -\mathrm{e}_g G \tag{38}$$

$$i_p = i_3 + i_4 + i_5 \tag{39}$$

where $g_2 = \dfrac{R_2}{\omega^2 L_2{}^2}$ and G[11] is the mutual conductance of the plate circuit.[12]

Substituting (33), (36), (37), and (38) in (39) we obtain

$$\mathrm{e}_g G + \mathrm{e}_p (g_2 + jb_2) - \mathrm{e}_g j\omega C_3 = 0 \tag{40}$$

where

$$b_2 = \left\{\omega(C_2 + C_3) - \frac{1}{\omega L_2}\right\}$$

Now substitute the value of e_p as given by (35) in (40), eliminate the voltage terms, and clear of fractions

$$j\omega C_3 G + g_1 g_2 + jb_1 g_2 + jb_2 g_1 - b_1 b_2 + \omega^2 C_3{}^2 = 0 \tag{41}$$

where

$$b_1 = \left\{\omega(C_1 + C_3) - \frac{1}{X}\right\}$$

[11] L. A. Hazeltine, Proc. I.R.E., 6, 63; April, 1918.
[12] Van der Bijl, "Thermionic Vacuum Tube," McGraw-Hill, 1918.

Generally $g_1\, g_2$ and $\omega^2 C_3^2$ are very small, and if we neglect them and equate the remaining real terms of (41) to zero in order to obtain the frequency of oscillation, we have

$$b_1 b_2 = 0 \tag{42}$$

If the values of b_1 and b_2 are substituted in (42) and this equation solved for ω^2 it is found that there are two possible frequencies given by

$$\omega_1^2 = \frac{1}{L\dfrac{C(C_1+C_3)}{C+C_1+C_3}} \tag{43}$$

and

$$\omega_2^2 = \frac{1}{L_2(C_2+C_3)} \tag{44}$$

Here ω_1^2 gives the frequency of the oscillations which are determined by the constants of the grid circuit. This frequency can be seen, by an inspection of (43), to be lower than the natural frequency of the crystal and mounting which is given by

$$\omega^2 = \frac{1}{L\dfrac{CC'}{C+C'}} \tag{45}$$

where the symbols are the same as used in Fig. 3.

This is seen to be due to the fact that the capacity C_1 (Fig. 7), is approximately equal to the sum of the grid-filament capacity of the tube and the shunt capacity of the crystal, C', of Fig. 3. Therefore the capacity term of (43) is greater than the corresponding term of (45). The result is that the frequency as given by (43) is lower than that given by (45).

It is very interesting to note that the input capacity of the tube enters into the frequency equations. This is in accordance with the predictions made after examining Fig. 5, and it may account for certain variations in the frequency of crystal oscillators, which are used as standards of frequency, when the tubes are changed.

The condition for the starting of oscillations is obtained from the imaginary terms of (41) by writing

$$\omega C_3 G + b_1 g_2 + b_2 g_1 = 0 \tag{46}$$

Substituting the values of b_1, b_2, g_1, and g_2 in (46), solving for G and neglecting certain very small quantities the condition for oscillations of the frequency given by (43) to occur is that

$$G=\frac{RC^2C_4(LC_4-L_2C_5)}{LL_2C_3(C-C_4)^2} \tag{47}$$

where $C_4=\dfrac{C(C_1+C_3)}{C+C_1+C_3}$ and $C_5=(C_2+C_3)$.

Now G cannot become negative, so $LC_4 \geqq L_2C_5$, but because $(C-C_4)^2$ is so very small there is practically only one adjustment which satisfies the condition that the value of G given by (47) must not be negative or greater than that obtainable from the vacuum tube. In addition the oscillations will be stronger when G is a minimum,[11] which occurs when

$$LC_4=L_2C_5 \tag{48}$$

Similarly the condition for the starting of oscillations of a frequency as given by (44) can be shown to be

$$G=\frac{R_2C_5\,(L_2C_5-LC_4)}{L_2C_3\,(C+C_1+C_3)} \tag{49}$$

where $C_4=\dfrac{C\,(C_1+C_3)}{C+C_1+C_3}$ and $C_5=(C_2+C_3)$.

In (49) the minimum value of G occurs when

$$L_2C_5=LC_4 \tag{50}$$

A comparison of (48) and (50) shows that the strongest oscillations occur when ω_1^2 is equal to ω_2^2. For all practical purposes the circuit of Fig. 7 can be considered to oscillate at only one frequency.

These conclusions agree with experiment, for it is well known that in tuning a crystal oscillator, Fig. 1, the load in the plate circuit should be adjusted so that its reactance is inductive, and then, when oscillations start, adjusted for maximum output, which is obtained when the plate circuit load is approximately in resonance with the crystal frequency.

We also know, from experimental evidence, that the emitted frequency of a crystal-controlled oscillator, Fig. 1, depends to a certain extent upon the circuit and tube as well as upon the

dimensions of the crystal. If a given crystal and holder are used, in a circuit such as shown in Fig. 1, to control the output of a commercial type UX201A tube, the frequency of the crystal-controlled output will be higher than if the same crystal is used to control the output of a Navy type CW1818A tube connected to an exactly similar circuit. This is believed to be due to the fact that the input capacities of the two tubes are different. This change in the frequency of the output could have been predicted from an examination of (43).

Another effect, which has not been mentioned so far and which causes changes in the generated frequency of a crystal oscillator, is that of temperature and its relation to the frequency of vibration of a quartz crystal. An increase in the temperature of a crystal causes the constants α, β and γ to change in such a manner that the generated frequency of the crystal-controlled oscillator is lowered. A decrease in temperature causes an increase in the frequency of the oscillator.

The effect of temperature upon the output frequency also depends on which axis of the zero-angle crystal is being used. If the frequency corresponds to vibrations of the crystal along the X axis, the temperature coefficient of frequency for the crystal, in a Navy type holder, is approximately twenty-five parts in a million per degree C. The temperature coefficient of frequency for Y axis vibrations is approximately fifty parts in a million per degree C., assuming the crystal is mounted in a Navy type holder.

The above discussion applies particularly to the case where the output of the crystal-controlled oscillator is desired to be of the same frequency as the crystal. In certain cases, however, we desire the fundamental crystal frequency and as many harmonics of this frequency as possible (as in the crystal-controlled calibrator). This can be accomplished by tuning the plate circuit by means of an inductance having a large L/C ratio. The harmonics are generated in the electrical circuit, and it should not be assumed that the crystal itself vibrates at the harmonic frequencies. In case it did, the harmonics would not necessarily be integral multiples of the fundamental, whereas the observed harmonics of a crystal-controlled calibrator are integral multiples of the fundamental crystal frequency.

When a crystal oscillator is used to control the frequency of the usual type of transmitter, and the emitted frequency is

an integral multiple of the crystal frequency, it does not follow that the desired harmonic present in the output of the crystal oscillator is picked up and amplified. On the contrary, except when the transmitter is operating at the crystal frequency, the crystal oscillator output excites a vacuum-tube frequency multiplier, which has its negative grid bias so adjusted and its plate circuit load so tuned that the desired frequency, which must be an integral multiple of the crystal frequency, is generated in the multiplier circuit.

Recent experiments have also shown that a crystal can be used to control the output frequency of an oscillator of the *relaxation* type so that crystal-controlled oscillations which are sub-harmonics of the fundamental crystal frequency can be obtained.

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FADING CURVES AND WEATHER CONDITIONS*

BY
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Summary—*Sunset fading curves from Station KDKA were made at Morgantown with a Shaw Recorder during April and May, 1927. The curves taken on fine days show more irregularity during the daylight hours than those taken on cloudy days. It was found that the signal strength from KDKA during the dark hours sometimes fell far below the daylight strength. A falling curve indicates clearing weather for the next day while a rising curve is followed by cloudy weather or rain.*

DURING the winter months, KDKA, the Pittsburgh Station of the Westinghouse Electric and Manufacturing Company, is very seldom in continuous operation through the sunset period. It is therefore possible to get only four curves a month showing the variation of strength in radio reception

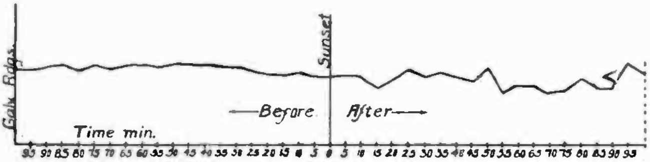

Fig. 1—KDKA at Morgantown; Generally Cloudy Days.

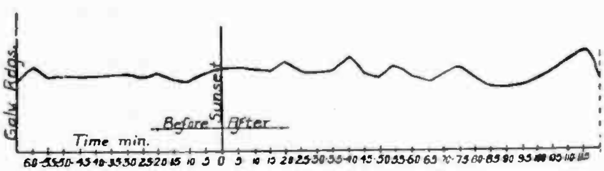

Fig. 2—KDKA at Morgantown; Generally Clear Days.

for an hour before and an hour after sunset. In the spring, however, on account of the longer days, it is comparatively easy to make records day after day throughout the sunset period. During April and May, 1927, thirty curves were taken on a Shaw Recorder throughout the sunset period. Eight of these curves were *undisturbed*, that is, they were fairly even during the period before sunset. Twenty-two of the curves were irregular during the daylight hours. Four of the undisturbed curves were taken on clear days and four on cloudy days. Of the *disturbed* curves

* Dewey decimal classification: R113.1. Original manuscript received by the Institute, October 30, 1928.

seventeen were taken on clear days and only five on cloudy days. This plainly shows the preponderance of irregularity on fine days.

The *undisturbed* curves were taken on April 4, 24, 1927, and May 2, 6, 7, 9, 11, 26, 1927. The *disturbed* curves were taken April 6, 11, 12, 13, 19, 20, 21, 22, 23, 25, 28, 30, 1927, and May 1, 3, 4, 5, 10, 12, 13, 14, 17, 27, 1927.

The galvanometer readings on the first eight curves were averaged at five-minute intervals measured from sunset as zero. The resulting curve is shown in Fig. 1. *Here it was noticed for the first time that the night reception from KDKA could fall below and remain below the daylight strength.* The twenty-two *disturbed*

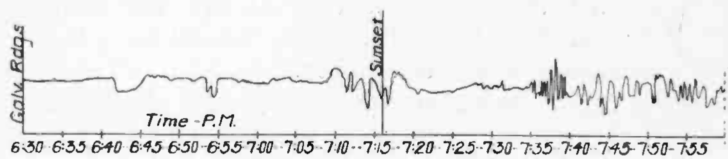

Fig. 3—Sunset Curve, KDKA, at Morgantown; Typical Cloudy and Cool. May 12, 1927.

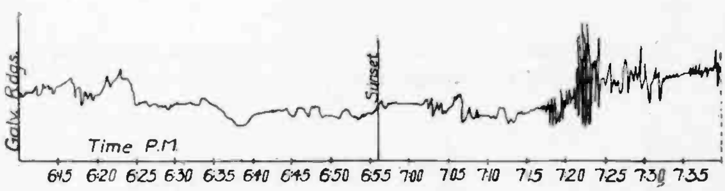

Fig. 4—Sunset Curve, KDKA, Morgantown; Typical Clear and Cool. April 23, 1927.

curves were averaged in the same way and the resulting curve is shown in Fig. 2. Fig. 3 shows a curve taken on the Shaw Recorder in which the night reception consistently falls below the day strength. Fig. 4 shows a curve in which the reception increases after sunset.

In the remaining figures, the upper curve in each case is that obtained on the Shaw Recorder while the lower curve shows the signal intensity obtained by averaging over five-minute intervals. That is, the whole curve is divided into five-minute intervals measuring from sunset or zero. The area of each interval is taken with a planimeter and the average ordinate calculated. The square root of the average ordinate gives the intensity

on an arbitrary scale. Fig. 5 shows an abrupt increase of intensity after sunset; while Fig. 6 shows a slight increase about an

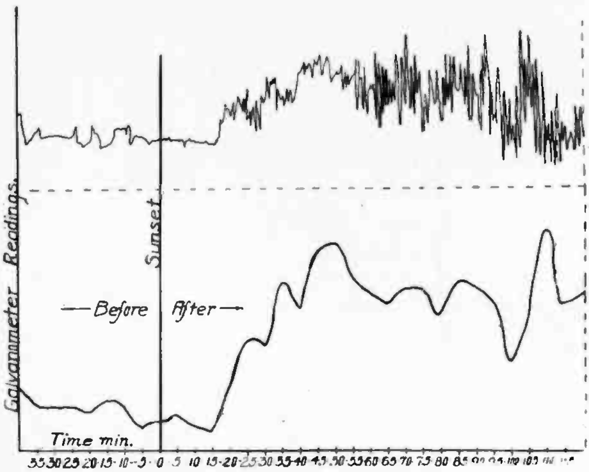

Fig. 5—Sunset Curve, KDKA, at Morgantown; Clear and Cool. April 11, 1927.

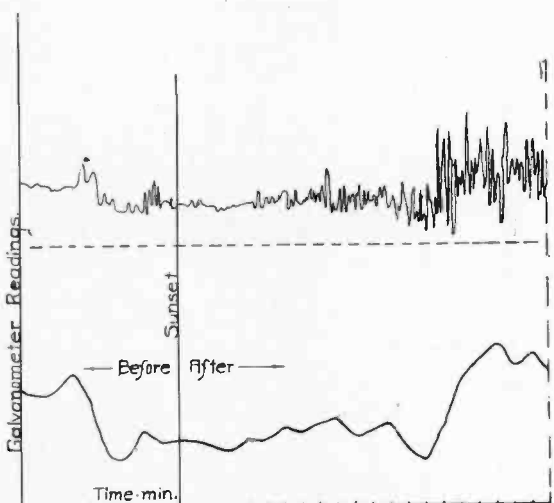

Fig. 6—Sunset Curve, KDKA, at Morgantown; Misting Rain. May 11, 1927.

hour after sunset. All the other graphs shown (Figs. 7 to 11) indicate a great reduction in signal strength after sunset.

Attempts were made to continue these observations during the summer and winter of 1927–28, but heavy static in the sum-

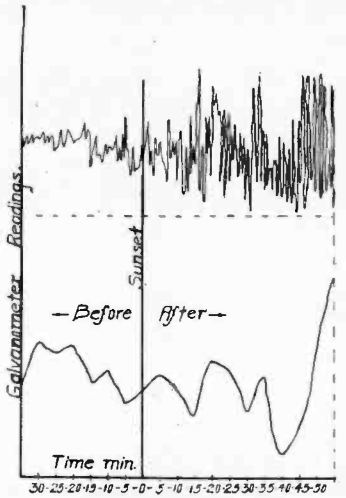

Fig. 7—Sunset Curve, KDKA, at Morgantown; Cool, Sunshine. April 6, 1927.

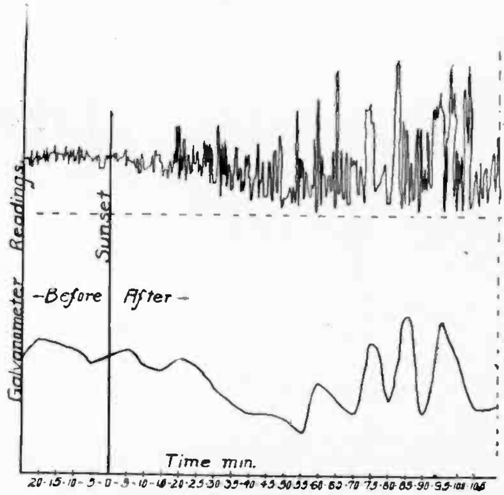

Fig. 8—Sunset Curve, KDKA, at Morgantown; Very Hazy, Temperature Pleasant. May 5, 1927.

mer of 1927 and interference from other stations during the winter prevented any continuous observations. However, the

summer of 1928 was singularly free from static and observations made then show that weather conditions have a decided effect upon the signals from KDKA. So much so that it is even possible

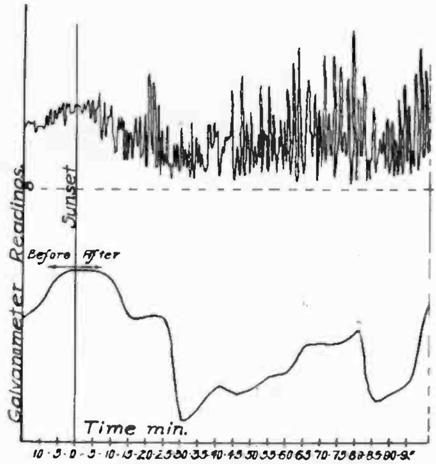

Fig. 9—Sunset Curve, KDKA, at Morgantown; Clear and Cool. May 13, 1927.

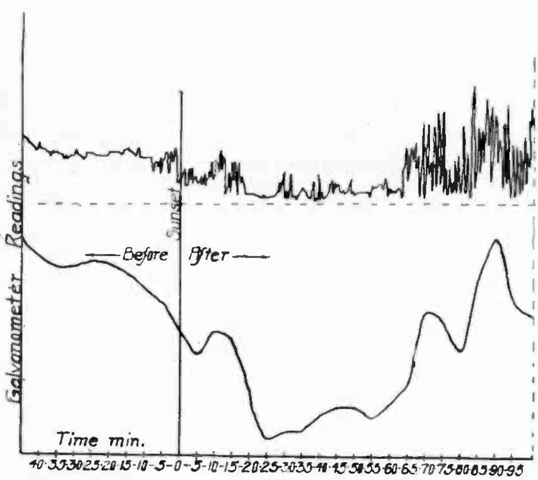

Fig. 10—Sunset Curve, KDKA, at Morgantown; Light Broken Clouds, Cool. May 14, 1927.

to foretell the weather one day ahead by the form of the fading curves. If the curve continues to rise after sunset, a wet or cloudy day is indicated; if the curve falls, the weather will tend

to clear. Thus Fig. 6 (upper curve) taken on a cloudy day shows that the following day, May 12, 1928, would also be cloudy at Morgantown. The curve of Fig. 5 taken on April 11,

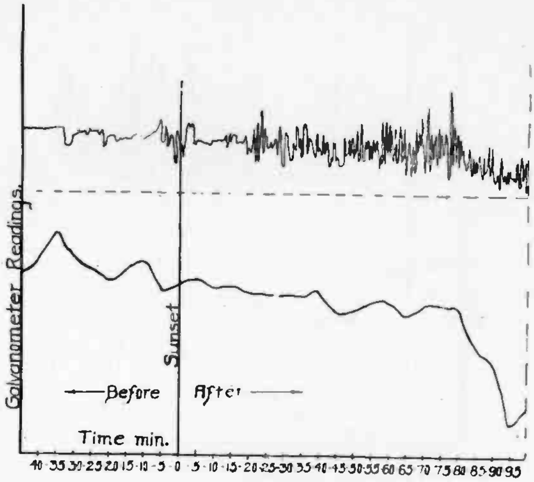

Fig. 11—Sunset Curve, KDKA, at Morgantown; Typical Cloudy and Cool. May 12, 1927.

1927 indicated that April 12 would be cloudy; April 12 was a cloudy day.

From Figs. 4 to 11, the captions "Galvanometer Readings" at the left refer to the upper curve only. The lower curve is the intensity of the signal averaged over five-minute intervals.

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DETECTION CHARACTERISTICS OF THREE-ELEMENT VACUUM TUBES*

BY

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Summary—*The change of grid potential in a grid-leak grid-condenser detector can be determined by considering a fictitious "rectified voltage" acting in series with the grid resistance. This equivalent voltage is inversely proportional to the tube "voltage constant" v, which has the value $v=2\ R_g/(dR_g/dE_g)$, and can be readily measured by an a.c. resistance bridge.*

The rectifying action of different tubes can be compared on the basis of the respective voltage constants at grid resistances inversely proportional to the size of grid condenser. Tubes are then compared under conditions of equal detector distortion, and the change of grid potential is inversely proportional to the voltage constants.

The voltage constant of ordinary vacuum tubes at first drops rapidly as the grid resistance is increased, but soon flattens out and becomes constant at grid resistances above 50,000 to 150,000 ohms.

The highest audio frequency that can be satisfactorily reproduced with the detector adjusted to full sensitivity is inversely proportional to the grid resistance at the lower end of the flat part of the $v-R_g$ characteristic.

It was found that tubes of the same type had uniform detection characteristics, that age, use, plate voltages between 16 and 122, and filament voltage (above the minimum necessary to give electron saturation) had little or no effect on the rectifying ability of high vacuum tubes at a given grid resistance in the useful range of operation.

Detector tubes best suited to resistance coupling are types 102-D, 240, and 200-A, because of their high μ and low v. The best detector from the point of view of power output and quality is the 227 type because of its low voltage constant and high amplification. Next in merit comes a group composed of types 112-A, 226, and 12. The sensitivity of the 200-A alkali vapor tube is substantially that of the corresponding high vacuum tube with the same μ.

DETECTOR CONSTANTS AND THEIR MEASUREMENT

IN the grid-leak grid-condenser detector the radio-frequency signal voltage is rectified in the grid circuit of the detector tube. This rectified grid current in flowing through the grid leak-condenser impedance produces a voltage drop which affects the plate circuit of the tube by amplifier action. In a previous paper[1] it was shown that the rectified current could be considered as produced by a series of fictitious generators acting between the grid and filament in series with the dynamic grid resistance. The voltage of these generators, conveniently called the "rectified

* Dewey decimal classification: R134. Original manuscript received by the Institute, September 5, 1928.

voltage," depends only upon the signal voltage and a single tube constant.

Detector problems can accordingly be conveniently analyzed with the aid of the equivalent detector circuit of Fig. 1, in which the rectified grid voltage E_r acts in series with the grid resistance R_g, and the grid leak-condenser combination shunted by the tube input capacity C_g' to the rectified current. The voltage produced across the grid leak-condenser impedance by the rectified grid voltage is the change of grid potential which affects the plate current by amplifier action.

Two detector constants suffice to give the complete performance of the detector. The first of these, the grid resistance R_g, is the reciprocal of the slope of the grid current-grid voltage characteristic at the operating point, and is required in setting up the

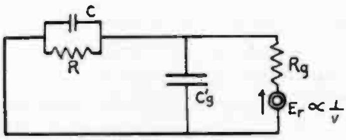

Fig. 1—Equivalent Circuit of Grid-Leak Grid-Condenser Detector.

equivalent detector circuit. The second constant determines the rectified grid voltage, and depends upon the grid resistance and the rate of change of grid resistance with grid voltage at the operating point. This constant has the dimension of a voltage, and so is called the voltage constant. It is defined by the relation

$$\text{Detector voltage constant} = v = \frac{2R_g}{\dfrac{dR_g}{dE_g}}$$

The rectified grid voltage is inversely proportional to v, so that a small voltage constant is desired. In the important case of a signal carrier wave of amplitude E_s modulated to a degree m, the modulation frequency component of rectified voltage has the amplitude mE_s^2/v.

To measure v one determines R_g first at the operating grid potential, and then at grid voltages above and below this operating point by a small amount ΔE_g, thus giving dR_g/dE_g. These three measurements of grid resistance give the entire detector performance, and can be easily and rapidly carried out with the alternating-current bridge arrangement described in the previous paper.

In using the bridge method of measuring v and R_g it is easier to manipulate the apparatus when the 1000-cycle input to the bridge is large, and when the grid-voltage increment ΔE_g is considerable, but increasing these quantities beyond a certain point introduces errors. A study was accordingly made to determine the most satisfactory values to use in making measurements.

It was found that the observed values of v become progressively lower than the true values as ΔE_g is increased, and for a given ΔE_g the error is greater for tubes with a small voltage constant. Mathematical analysis based on observed detector characteristics shows that over the range of grid voltages for which v is substantially independent of grid resistance (see Fig. 2 for example) values of ΔE_g such that $\Delta E_g/v=0.2$ lead to an error of less than 3 per cent. Larger voltage increments than this rapidly increase the error. Over the part of the tube characteristic where v decreases with increase of grid resistance the allowable $\Delta E_g/v$ is about half that permissible over the flat portion. As most tubes have a voltage constant v lying between 0.2 and 0.5 volt over the flat portion, and more over the dropping part, values of 0.05 volt and less for ΔE_g should give satisfactory results, and experiments show this to be the case.

The effect which the bridge input voltage has on the dynamic grid resistance as measured by the bridge depends primarily upon the purity of wave form of this voltage. The indications are that with a pure sine wave, the bridge input could be at least 0.1 volt effective in most cases. With harmonics present the bridge input must be smaller in proportion. The measurements reported in this paper were made using power from a master-oscillator power-amplifier vacuum-tube generator, and with the outfit loaded fairly heavily a bridge input voltage of 0.025 effective was about the maximum allowable because of harmonics. Errors due to excessive bridge inputs can be readily detected by noting whether or not the balance is affected by lowering the input.

Basis for Comparing Detectors

In comparing different grid-leak grid-condenser detectors it is necessary to separate the rectifying and the amplifying action. The change of grid potential is given by the equivalent circuit of Fig. 1 and is determined by the rectifying action in the grid, but

[1] F. E. Terman, "Some Principles of Grid-Leak Grid-Condenser Detection," Proc. I. R. E., 16, 1384; October, 1928.

the effect which this has on the plate current is purely an amplifier problem.

The criterion for comparing the rectifying action of different detectors when used with the same size grid condenser is the value of the voltage constant v at a given grid resistance. *The change of grid potential produced by a given signal is inversely proportional to the voltage constant v when the grid resistance R_g and the size of grid condenser are fixed.*[2]

It is well-known that the higher modulation frequencies do not give as great a change of grid potential as the lower frequencies, and the magnitude of this effect depends upon the grid resistance at the operating point and the size of grid condenser.[3] *Where the same grid condenser is used, detectors compared at the same value of grid resistance will be compared under conditions of equal distortion.*

The best size of grid condenser is approximately ten times the effective grid-filament tube capacity to radio frequencies, so will tend to vary with different types of tubes. Detectors with different grid-condenser capacities must be compared under conditions which give the same distortion at the higher modulation frequencies, *and so are compared on the basis of the voltage constant v at grid resistances inversely proportional to the grid condenser capacity.* This gives a comparison under conditions of equal distortion, and under such circumstances the change of grid potential produced by the signal is inversely proportional to the voltage constant, so that *the tube with the smallest v gives the greatest change of grid potential.*

The overall performance of a detector depends upon the change of grid potential, the criterion for which has already been given, and the amplification of this grid voltage. Unfortunately, there is no simple physical quantity that correctly gives a figure of merit for the entire detector action, and for the present the two functions will be considered separately.

[2] This statement and the similar italicized phrases in the next two paragraphs assume that the grid-leak resistance is so high as to have negligible effect on the voltage drop across the grid leak-condenser impedance. The exact statement is that *for equal* distortion the conductance of the grid resistance and the grid-leak resistance in parallel should be proportional to the effective grid-condenser capacity. The conductance of the grid-leak resistance is ordinarily so small that for most uses the exact rule is not necessary.

[3] For an exact analysis see Terman, l.c.; or Ballantine, "Detection by Grid Rectification with the High-Vacuum Triode," Proc. I. R. E. 16, 593; May, 1928.

RESULTS OF TESTS ON HIGH-VACUUM DETECTORS

General. Tests of numerous types of tubes under a wide variety of conditions *in every instance* gave a relationship between voltage constant v and grid resistance R_g of the general form shown in Fig. 2, in which with increasing grid resistance the voltage constant rapidly drops to a substantially constant value that continues up to the limit of the measuring equipment used, which was about two megohms. The principal differences observed between individual tubes, types of tubes, and battery potentials were in the value of voltage constant over the flat part of the curve, the grid resistance where the curve flattened out, and the grid voltage required to give a specified grid resistance.

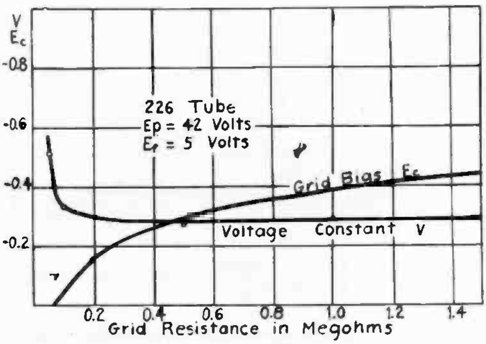

Fig. 2—Rectifying Characteristics of Typical Detector Tube.

In considering the significance of Fig. 2, it is to be remembered that for good quality telephone reception with standard tubes the grid resistance must be between 100,000 and 200,000 ohms. The exact value to use depends upon the allowable distortion at the high modulation frequencies and can be computed with the aid of the equivalent detector circuit of Fig. 1. In code reception, grid resistances several times the values most suitable for telephone reception are preferable. The important operating range of the detector is hence at grid resistances in the range from 100,000 to 500,000 ohms. The essential points to observe in comparing the detector action of different tubes are (1) the value of voltage constant over the flat part of the characteristic, and (2) the grid resistance at which the characteristic becomes flat.

Comparison of the Detector Action of Tubes of the Same Type under the Same Conditions. It was found that the $v-R_g$ characteristic of different tubes of the same type, operated at the same

plate and filament voltages, was consistently uniform. The value of voltage constant v over the flat part of the characteristic for an individual tube practically never departs over 15 per cent from the average value of all tubes.

The principal individual difference between tubes is in the value of grid voltage required to give a given grid resistance. There were also some differences between tubes in the grid resistance at which the characteristic became flat, and in the characteristic before the flat portion was reached.

A typical comparison of several tubes of the same type is given in Fig. 3. The detection characteristics of individual tubes appear to be about as uniform as plate resistance, plate current, etc. This was found true for all types of tubes tested.

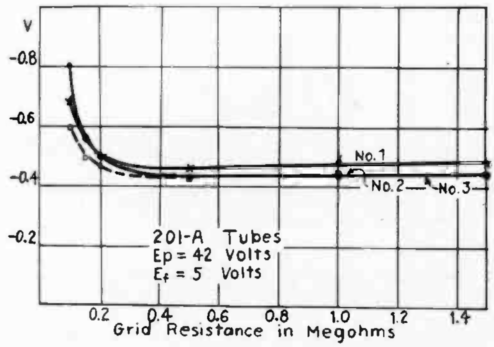

Fig. 3—Comparison of Three 201-A Tubes.

Effect of Filament Voltage. Substantially the only effect of changing the filament voltage of a tube is to alter the grid voltage at which a given grid resistance is obtained, this grid voltage being more negative at the higher filament temperatures. *The voltage constant v at a given grid resistance is roughly independent of filament voltage until the electron emission has dropped to the vicinity of the saturation value.* The results presented in Fig. 4 are typical of all tubes. In general the part of the characteristic before the flat part is much more influenced by electron emission than is the flat portion, and as the filament voltage is reduced the effect is noticed at the lower values of R_g before becoming evident at high grid resistances. The minima of v seen in Fig. 4 are found in all tubes.

Effect of Plate Voltage. Variations in plate voltage between about 16 and 122 volts have practically no effect on the value of voltage con-

stant v at a given grid resistance provided this grid resistance is on the flat part of the $v-R_g$ characteristic. If on the dropping part, the voltage constant decreases slowly with increase of plate voltage. The results of Fig. 5 are typical. For the tube shown, the curve for $R_g=100{,}000$ ohms is the only one not on the flat part. The principal effect of increasing the plate voltage is to make a more positive grid necessary for a given grid resistance.

At very low plate voltages the detector voltage constant is somewhat erratic in its behavior, but is in general rather small, indicating good rectification. Some tubes, such as the 227 heater tube will actually rectify about as well with zero plate volts as at any voltage.

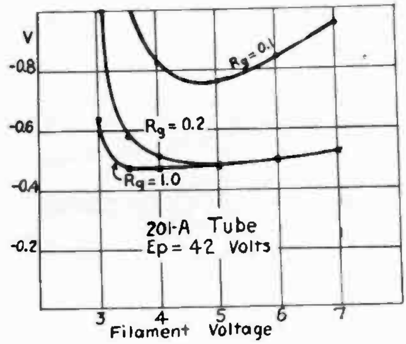

Fig. 4—Effect of Filament Voltage on Detector Voltage Constant.

Effect of Age. Age or use seems to have no effect on the $v-R_g$ characteristic of detectors provided the electron emission is sufficient. Tubes that had been used hundreds or thousands of hours, and even tubes that had been rejuvenated several times tested substantially the same as new tubes.

TABLE I

AVERAGE DETECTION CHARACTERISTICS OF TUBE TYPES

Type	Number tested	v (flat part)	R_g at start of flat part (approximate)	μ	R_p (45 volts)	Highest undistorted frequency
201-A	7	0.47	150,000	8	14,000	3,500
200-A	3	0.47	50,000	20	30,000	11,500
240	2	0.47	150,000	30	150,000	3,500
199	6	0.50	125,000	6	17,000	4,250
120	6	0.45	125,000	3	8,000	4,250
171-A	4	0.28	200,000	3	2,500	2,600
112-A	5	0.26	150,000	8	9,000	3,500
226	7	0.29	150,000	8	9,000	3,500
227	6	0.23	50,000	8	10,000	11,500
12	2	0.26	50,000	6	17,000	11,500
102-D	3	0.27	100,000	30	90,000	5,300
310	1	0.45	150,000	8	10,000	3,500

Note: Values for v are average over entire flat portion for tubes listed as tested.

All tubes made by R.C.A. except 102-D which is a Western Electric tube.

Highest undistorted frequency is highest frequency reproduced at least 70 per cent as well as low notes with grid condenser plus tube input capacity of 300 $\mu\mu$f.

Comparison of Tube Types. The results of an extensive series of tests are presented in Table I. The figures given for each tube type represent the average of all tubes of that variety tested. Individual readings practically never differed by more than 15 per cent from the means tabulated for the voltage constant v.

The rectifying ability (i.e. the change of grid potential produced by a given signal) of the different tubes of Table I can be directly compared at the same grid resistance because the grid-filament tube capacity of all types shown is so near the same as to make it common custom to use the same grid-condenser capacity in all cases. When operated at grid resistances that are in the flat part of the characteristic, the rectifying ability is inversely

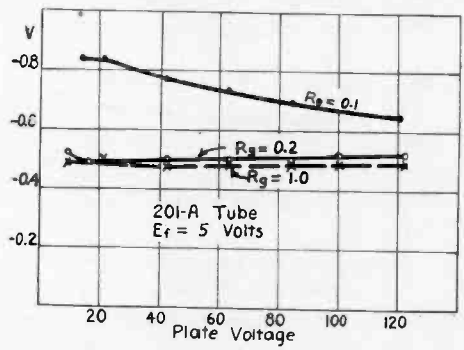

Fig. 5—Effect of Plate Potential on Detector Voltage Constant.

proportional to v, so that the tube with the smallest v (the 227 type) gives the greatest change of grid potential with a given signal, and the tube with the largest v (the 199 type) gives the smallest change of grid potential.

The actual sensitivity of a tube acting as grid leak-condenser detector depends not only upon the rectifying ability of the tube, but also upon the extent to which the change of grid potential is amplified. Thus in 199 tube is not as sensitive a detector as the 201-A type because although both have substantially the same voltage constant, the 201-A type is a better amplifier because of its higher μ and lower plate resistance.

The values of voltage constant v given in Table I for the flat portion of the $v-R_g$ characteristic apply for all plate voltages above 16 volts up to at least 122 volts (or until the plate current is excessive, as in low μ tubes), and for all filament voltages above those giving electron

saturation. The value of grid resistance at which the flat part of the $v-R_g$ characteristic begins is lowered very slightly by increasing the plate voltage, and also, at least up to a certain point, by increasing the filament voltage.

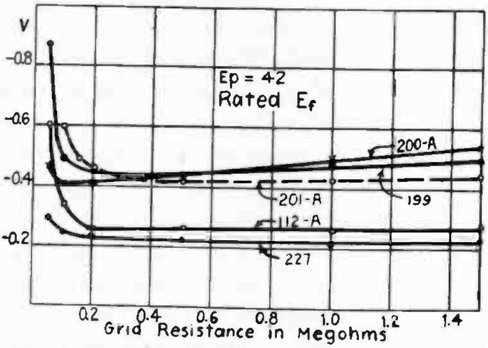

Fig. 6—Detecting Characteristics of Typical Types of Tubes.

A comparison of the rectifying ability of the principal detector tubes now in common use is given in Fig. 6, which includes a typical representative of each type.

The Type 200-A Alkali Vapor Detector. Although this tube contains gas its characteristics are very similar to those of high

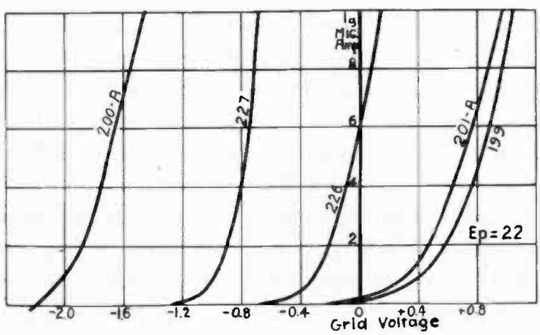

Fig. 7—Grid-Voltage Grid-Current Characteristics of Standard Tubes.

vacuum tubes, as evidenced in Fig. 6. The characteristics of the 200-A tube change a little with variations in plate voltage, but seem to be unaffected by moderate use, or by filament temperatures provided electron saturation is present. The voltage constant of the alkali vapor tubes is constant above a grid resistance of less than 50,000 ohms.

As a rectifier the alkali vapor tube is almost exactly the same as the 201-A tube, all superiority of the 200-A tube as a detector coming from its higher μ, and from the fact that its wide range of the flat part of the characteristic makes possible high-quality reception without impairment of sensitivity.

The Grid-Voltage Grid-Current Characteristic. The grid-voltage grid-current characteristic of different tube types is similar in general form, but differs in steepness, and in location along the grid-voltage axis, as shown in Fig. 7.

The more sharply the curve bends upward the smaller the voltage constant v and the better the detector. Displacement along the grid-voltage axis is of no importance other than affecting the grid leak required to give a desired operating grid resistance. It will be observed that the tubes with the lowest cathode voltage drop are generally farthest to the left, as one would expect. Decreasing the plate voltage, or increasing the filament voltage, displaces a curve to the left without materially altering its shape. At very negative grid voltages the grid-current of the 200-A tube is seen to go through zero and reverse as a result of ionization.

Discussion

The conclusions of this paper are based on approximately one thousand separate measurements of detector voltage constant v, of which about one third were of an exploratory nature, and are not used in the final results. These measurements were on the average correct to probably five per cent. The results on the same tube taken at different times on the same set-up always agreed within this limit, as did results taken on three different bridge outfits, two of which used the Wagner earth connection while the other did not. If desired, the precision could be greatly improved, but for this study it was preferred to make a large number of measurements of fair accuracy rather than a few very correct ones.

A number of integrity tests were made to check the accuracy of measurements and the correctness of the general theory. These were made by applying a known unmodulated signal to the grid leak-condenser detector when at a known operating point, and measuring the change of plate current. Measured values averaged 5 per cent above the predicted theoretical quantities, with a maximum variation about this mean of approximately 5 per cent.

The grid resistance at which the flat part of the $v-R_g$ characteristic begins is one of the most important properties of a detector

tube, as it determines the highest audio frequency that the grid leak-condenser detector can reproduce at full sensitivity. The detector voltage constant v increases in value so rapidly as the grid resistance is lowered below the limit of the flat portion that operation much below the bend of the curve is entirely impractical because of the great loss in sensitivity. The end of the flat part of the $v-R_g$ characteristic therefore sets the minimum grid resistance that will give satisfactory sensitivity, and this minimum grid resistance fixes the highest audio frequency that can be reproduced without undue distortion. The last column of Table I gives the highest audio frequency that is reproduced at least 70 per cent as well as the low notes when the operating point is at the grid resistance marking the end of the flat part of the $v-R_g$ characteristic, and the conventional size grid condenser is used.

The points which it is desirable to incorporate in a detector are: (1) a small value of voltage constant v, which gives a large change of grid potential with a given signal; (2) a $v-R_g$ characteristic which is substantially flat, or at a minimum, at grid resistances in order of 100,000 ohms; and (3) a high amplification of the change of grid potential. It is also helpful to have a small inter-electrode capacity in order to permit the use of a small grid condenser. The amplification of a tube is proportional to $\mu/\sqrt{R_p}$ where power output is desired, but is proportional to μ in the case of resistance or impedance-coupled amplifiers.

The selection of a grid leak-condenser detector tube depends upon the circuits involved. When compared on the basis of the audio-frequency power output obtained from a given signal, and disregarding quality, the figure of merit is $(\mu / \sqrt{R_p}) / v$. On this basis the 227 heater type tube is very definitely superior to all other standard receiving tubes. The types 112-A, 226, and 12 are approximately tied for second place, and are followed by a third group made up of types 240, 171-A, and 200-A. The next group includes types 201-A and 199, while the 120 type is the poorest detector of the entire group. If quality of output is taken into account the types 227, 12, and 200-A gain an additional advantage over the rest. When resistance-coupled amplification is used the figure of merit is μ/v, making types 102-D, 240, and 200-A preferred in the order named. It is worth noting that the 112-A tube is very superior to the 201-A type as a detector when both are at the same plate voltage and filament power.

A comparison of tube types 201-A, 240, and the gaseous 200-A

indicates that a tube similar to the 201-A or the 240 but with $\mu = 20$ would have almost exactly the same voltage constant v as the 200-A. The alkali vapor in the 200-A tube would therefore seem to be of no advantage except insofar as it extends the flat portion of the $v - R_g$ characteristic into low grid resistances.

The best plate voltage to use on a detector is ordinarily the highest available, subject to the limitation set by the allowable plate current. At least 45 volts should always be used, and generally 67 to 90 is better. A high plate voltage lowers the plate resistance and does not affect the voltage constant at a given grid resistance. Only in the case of resistance or impedance coupling is the plate voltage unimportant.

The filament voltage is relatively unimportant provided it produces sufficient electron emission to give saturation.

The grid resistance at which the detector operates is determined by the grid-leak resistance and the potential of the grid return lead. The operating point can be conveniently controlled by the resistance of the grid leak.

After considering the detector characteristics of tubes now available one naturally wonders just what design and construction features give a sensitive detector tube. While the results of this paper do not answer this question, analysis of the data does indicate that voltage drop in the filament,[4] type of filament (oxide or thoriated), power rating of tube, and changes in μ are not the most important elements. An investigation is now being made into this and other features of detectors, and it is hoped that definite conclusions can be reported at some future date.

The authors wish to acknowledge their appreciation of the assistance rendered by Messrs. R. Whittern and E. R. Adams in supplying the vacuum tubes used in this study.

[4] The general tendency is for oxide coated filament detector tubes to be superior to other types, but there is a wide variation in oxide coated filaments, some of which (as a J tube tested) have voltage constants of over 0.40 volt.

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FILTERING ANTENNAS AND FILTER-VALVE CIRCUITS*

By
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Summary—*Some methods of coupling together many circuits or antennas giving them simultaneous excitation from the same source of energy are described. The purpose of such arrangements is the construction of practical filter circuits (filtering antennas) giving square-topped resonance curves with good efficiency. Some interesting phenomena with coupled antennas are described.*

THE importance of square-topped resonance curves in the field of wire telephony was recognized many years ago. Many useful circuits have been developed and constructed by Campbell and others. The importance of square-topped resonance curves for radio work has often been discussed and described. The Marconi Wireless Telegraph Company, Ltd., has used some filters of this kind in their commercial receivers;[1] other companies have probably made use of them also.

In radiotelephony, especially with broadcast receivers, "square-topping" did not attract much attention, since more pronounced and more obvious problems were considered more important at the moment.

F. K. Vreeland[2] has reported some filter circuits in his design for receivers, giving square-topped resonance curves and pointing out their usefulness for distortionless reception of a modulated wave. The author has been interested in this problem for a long time, and has also developed some interesting circuits and antenna arrangements[3] which will be described herein. As the importance of such curves is recognized, the author will limit this paper to the special arrangements developed by him. The filter circuits which were developed consist of resonant circuits coupled together and simultaneously excited by the same source of energy

* Dewey decimal classification: R386. Original manuscript received by the Institute, December 28, 1927. Revised manuscript received June 12, 1928.

[1] See Marconi Pamphlet No. 230/2.

[2] F. K. Vreeland, "On the Distortionless Reception of a Modulated Wave and Its Relation to Selectivity," PROC. I.R.E., 16, 255; March, 1928.

[3] British Patents 211.151 (1923); 271414 (1926) French Patent. 576.785 (1923). U. S. A. Patent Serial No. 690.120.

(electromagnetic wave, anode circuit of a valve, etc.) The output connections are attached to one of the parallel circuits. The performance of this arrangement can be determined from the description given below.

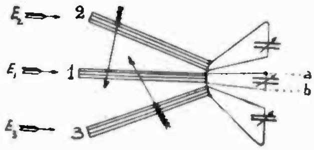

Fig. 1

If we have n antennas mutually coupled (see Figs. 1, 2, and 3) or resonant circuits which receive energy simultaneously from a high-frequency source (i.e., an electromagnetic wave), the differential equations of these circuits can be easily written and the solution indicates that in every circuit both forced oscillations of the same frequency as the source of energy and free oscillations will be generated. These free oscillations represent a number of different frequencies. As a result of the damping of the circuits, all free oscillations disappear after a short time, while the forced oscillations remain.

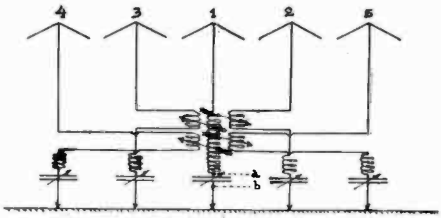

Fig. 2

It can be shown that the time of the disappearance of the free oscillations or the transitory condition of such circuits is shorter than that of ordinary series band filters.[4] The forced oscillations can easily be calculated by well-known methods. We shall first examine two parallel circuits or antennas excited simultaneously:

(1) for a constant incoming wavelength and variable tuning of the circuits, (2) for a variable incoming wavelength and constant tuning of the circuits.

Two Parallel Circuits or Antennas Coupled Together

It can be shown that if we have two circuits or antennas

[4] Campbell, Wagner.

coupled together the absorbed energies can be calculated by means of the following equations:

$$W_1 = (i_1)^2_{eff} \times R_1 = \frac{R_1}{2} \times \frac{(E_2 y - E_1 Z_2)^2 + E_1^2 R_2^2}{[Z_1 Z_2 - (R_1 R_2 + y^2)]^2 + (R_1 Z_2 + R_2 Z_1)^2}$$

$$W_2 = (i_2)^2_{eff} \times R_2 = \frac{R_2}{2} \times \frac{(E_1 y - E_2 Z_1)^2 + E_2^2 E_1^2}{[Z_1 Z_2 - (R_1 R_2 + y^2)]^2 + (R_1 Z_2 + R_2 Z_1)^2}$$

where

$$y = M\omega$$

$$Z_1 = \left(L_1\omega - \frac{1}{C_1\omega}\right) \quad Z_2 = \left(L_2\omega - \frac{1}{C_2\omega}\right).$$

For a constant frequency of the electromagnetic wave and constant tuning of the first circuit, the effect of the degree of

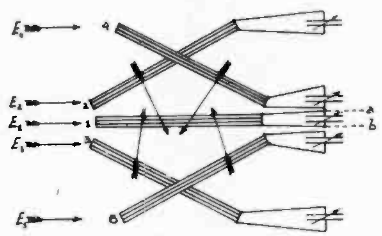

Fig. 3

coupling is very interesting when the tuning of the second circuit is made variable.

In Fig. 4 curves for two circuits are given. Power absorbed is plotted as a function of the tuning of the second circuit. The first circuit is tuned to the incoming wavelength, then it is coupled with the second circuit, which is then tuned by means of a tuning condenser. Near the resonance point of the second circuit we have a minimum of current in the first circuit, then a maximum, and the asymptotical currents decrease. The maxima and minima depend on the coupling. This phenomenon is clearly shown in Fig. 4. In the second circuit we have ordinary resonance curves, although the apparent resistance is higher.

Judging by these curves the current at its maximum in the first circuit coupled with the second circuit is greater than in the first circuit alone, not coupled with the second circuit. The mutual coupling of the two circuits reduces the apparent resistance of the first circuit. It is obvious that in this case the first

circuit receives energy not only from the electromagnetic wave, but also from the second circuit. From Fig. 4 we can easily calculate the efficiency of this arrangement, which can be exceedingly great (90 per cent or more).

In series filters the efficiency must be much less because the efficiencies of different chain members of the filter must be mul-

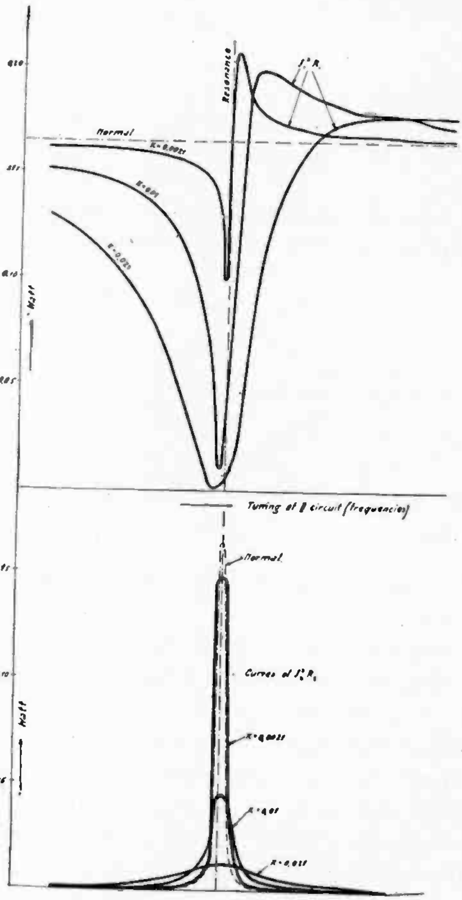

Fig. 4

tiplied in order to obtain the efficiency of the whole system. The over-all efficiency of a series filter is indeed very low (about 50 per cent), depending on the number of sections. It can also be shown that for several parallel circuits the same effects can be obtained, and that the efficiency of such filters is greater than

the efficiency of series filters. If the effective resistances of the two coupled circuits are different, very sharp resonance curves are obtained. The relation between minimum and maximum can be very great.

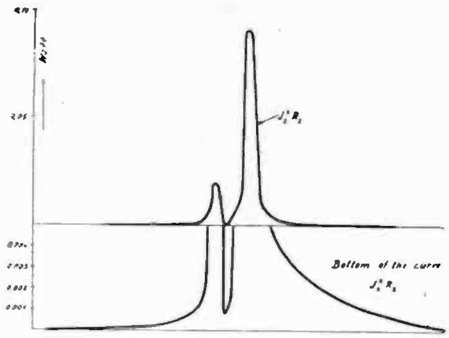

Fig. 5a

For all curves mentioned above it was assumed that the electromotive forces were equal. If they are much different we observe the ordinary effect of the two coupled circuits with an electromotive force in one of them. The more the electromotive force appears in one of the circuits the more the minima and maxima are smoothed out.

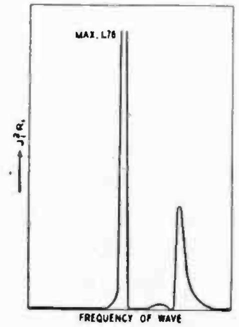

Fig. 5b

The above-mentioned effects could be obtained by exact calculation of the electrical values of the two circuits. It is obvious from the above-mentioned figure that the effective resistances of the two circuits must have the correct relation to the coupling degree of the two circuits.

$$\omega M \cong R_1; \omega M \cong R_2; R_1 \cong R_2$$

The position of minimum and maximum can be changed if we shift the coupling coil through 180 deg. or if we change the phase of the electromotive force by 180 deg. In this case we have first maximum and then minimum, if we go from a lower to a greater frequency.

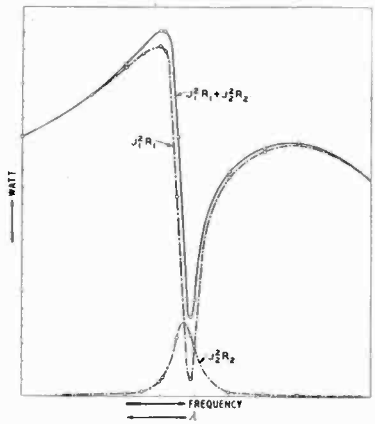

Fig. 5c

Constant Tuning of Circuit I and Circuit II with the Wavelength of the Electromagnetic Wave Variable

We take the same circuits as described in Fig. 4, and change the frequency of the oscillations. Again we obtain deformed resonance curves. The curve $J_1^2R_1$ has a flat minimum and a maximum. The curve $J_2^2R_2$ has two maxima and one minimum. In Fig. 5 the curves of $J_2^2R_2$ are represented. In Fig. 5b the curve of $J_1^2R_1$ is shown when $R_2 << R_1$. In Fig. 5c the curves of $J_1^2R_1$ and $J_2^2R_2$ are shown for circuits with $R_1 = R_2$ but with different values of C and L.

Three and More Circuits in Parallel

The calculation of mathematical figures for three and more circuits or antennas in parallel is very difficult as the corresponding figures are complicated. In order to facilitate this work we put some of the coefficients of mutual induction equal to zero. Such

a simplification of the problem is permissible because we can always construct an antenna or a circuit so that some of the coefficients of mutual inductance will equal zero. It is very difficult, often impossible, to construct three or more circuits with the same coefficients of mutual inductance.

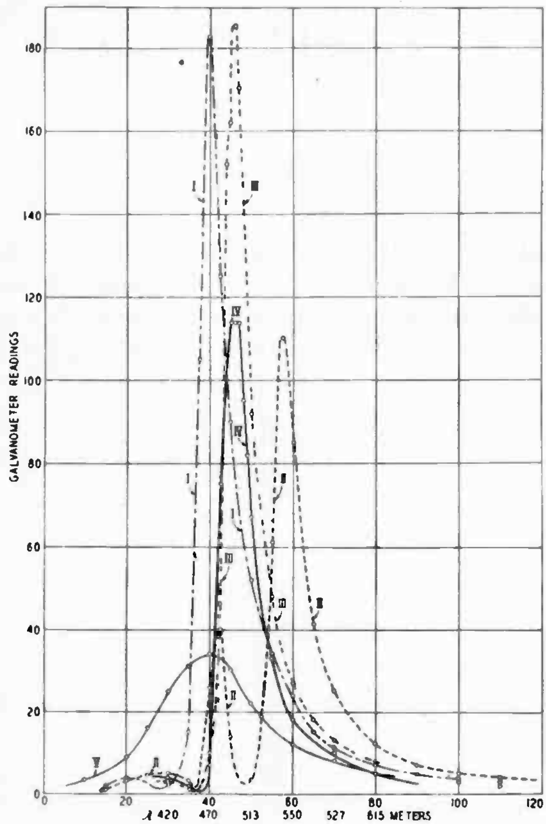

Fig. 6

Let us take the circuits as shown in Fig. 1; we can put $M_{23}=0$; that is, the coupling between the second and third circuits equals zero. We can obtain the same condition for more than three circuits. In this case the corresponding mathematical figures are deduced more readily.

If we have three circuits (Fig. 1), we can put $M_{23}=M_{32}=0$,

and we thus obtain the corresponding figure for absorbed energy:

$$W_1 = R_1 I_1{}^2{}_{eff} = \frac{1}{2} \times$$

$$\times \frac{R_1 \times \left\{ \left[E_1 - E_2 \dfrac{Z_2 y_2}{Z_2^2 + R_2^2} - E_3 \dfrac{Z_3 y_3}{Z_3^2 + R_3^2} \right]^2 + \left[E_2 \dfrac{y_2 R_2}{Z_2^2 + R_2^2} + E_3 \dfrac{y_3 R_3}{Z_3^2 + R_3^2} \right]^2 \right\}}{\left[R_1 + \dfrac{y_2^2 R_2}{Z_2^2 + R_2^2} + \dfrac{y_3^2 R_3}{Z_3^2 + R_3^2} \right]^2 + \left[-Z_1 + \dfrac{Z_2 y_2^2}{Z_2^2 + R_2^2} + \dfrac{Z_3 y_3^2}{Z_3^2 + R_3^2} \right]^2}$$

where

$$\begin{cases} Z_1 = \left(L_1\omega - \dfrac{1}{C_1\omega} \right) \quad Z_2 = \left(L_2\omega - \dfrac{1}{C_2\omega} \right) \quad Z_3 = \left(L_3\omega - \dfrac{1}{C_3\omega} \right) \\ y_2 = M_{12}\omega, \quad y_3 = M_{13}\omega \end{cases}$$

We shall now study the change of currents: (1) for a given wavelength of the electromagnetic wave, and (2) for a given tuning of the three circuits as a function of a variable wavelength of the received wave. For a constant frequency of the wave with

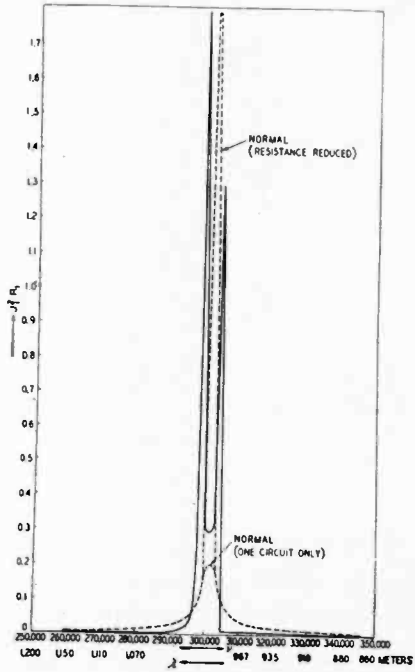

Fig. 7

the first and second circuits tuned to maximum current in the first circuit and variable tuning in the third circuit, a phenomenon similar to that of two circuits in parallel is obtained; there is a minimum, a maximum, etc.

For a Variable Frequency of Wave and Constant Tuning of the Three Circuits

Here we attain very interesting curves. Let us discuss a practical case (Fig. 6). We have frame aerials (closed circuits) as indicated in Fig. 1. The first frame was connected to a galvanometer through a detector. The second and third frames were removed and Curve V was taken for the first frame by changing the heterodyne frequency; that is an ordinary resonance curve. After this the second frame was coupled with the first and adjusted in order to give the maximum of current in the

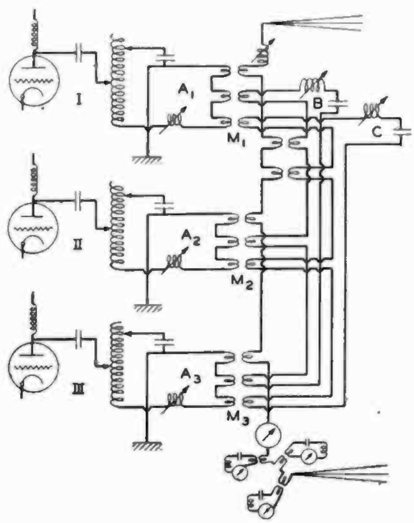

Fig. 8

first frame for $\lambda = 470$ meters. Then the third frame was coupled and adjusted to obtain still more current in the first frame. This done the curve for the current of the first frame was checked (Curve I). Then the second frame was slightly detuned by increasing its capacity about three per cent and the third frame detuned by diminishing its capacity about three per cent. The corresponding curve has two maxima (Curve II). If the detuning of the second and third frames is diminished a setting can thus be obtained where Curve IV appears, and the filtering effect of this arrangement becomes evident. This arrangement received with uniform intensity a band of frequencies approximately 20,000 cycles wide. The frequencies lying outside this band are

strongly damped; Curve IV on either side of the drawing goes below Curve V. If the detuning of the second and third frames is further diminished, Curve III is obtained, which is similar to a normal resonance curve. It must be pointed out that all curves have a pronounced minimum. It is obvious that with five and more circuits still better results can be obtained.

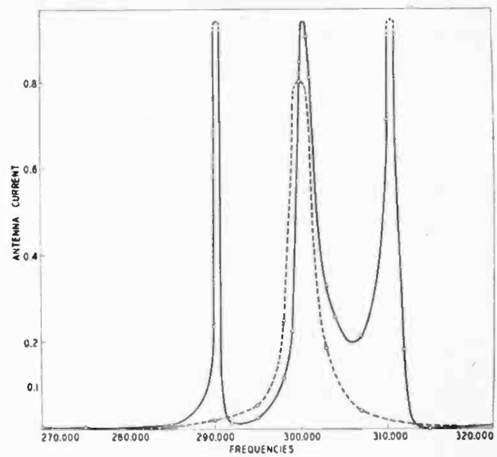

Fig. 9

Taking three frames, with the second and third having resistances equal to zero by reaction, a resonance curve is obtained, as in Fig. 7. That is an inverted resonance curve.

The same arrangement can be used for a multiplex transmitting system in wireless telephony and telegraphy.

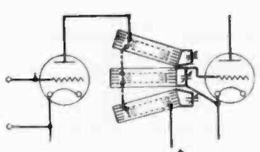

Fig. 10

Fig. 8 shows a system of multiplex transmission. A radiating antenna is coupled with two closed circuits B and C, influenced by a transmitter's intermediate circuit A_1 and coupling M_1. The intermediate circuit influences at the same time the two closed circuits B and C; transmitter I excites the antenna by the intermediate circuit A_1 and allows radiation of energy on a wave λ_1.

Transmitter II acts by the intermediate circuit A_2 and coupling M_2 upon the same aerial and the same coupled circuits B and C. It is possible in this way to transmit on the same antenna a second wave λ_2. Transmitter III acts by the intermediate circuit A_3 and coupling M_3 upon the antenna and the same closed circuits B and C, allowing transmission of a third wave λ_3. In

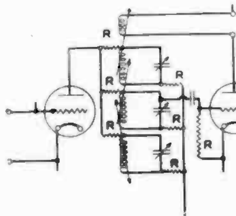

Fig. 11

such a manner it is possible to transmit simultaneously many waves from one radiating antenna. If in general there are $(n-1)$ closed circuits coupled with the antenna, n messages can be transmitted simultaneously.

With correct tuning of the coupled circuits a band of frequencies amounting approximately to 10,000 cycles will be radiated in a square-topped resonance curve. (Fig. 8) In this case we

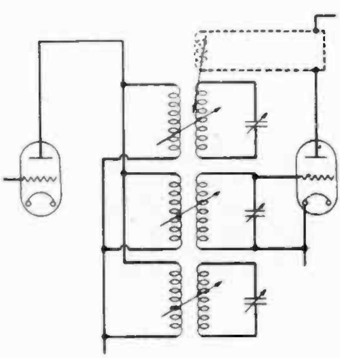

Fig. 12

must have some independent drive circuits connected to the grids of amplifying valves in such a way that the modulated wave will be transmitted by the antenna system without distortion. If multiplex transmission is to be obtained by the arrangement shown in Fig. 8 many drivers tuned to the respective wavelengths of the antenna system are required. In this case the

characteristic curve of the antenna will be as indicated in Fig. 9. The curve shown by dotted lines is the resonance curve of the antenna with circuits *B* and *C* removed.

It is possible to use one driver circuit and one amplifying system together with the antenna system described. In case of modulation of the wave by many frequencies (acoustic or supersonic) so that the resulting modulation waves are in resonance

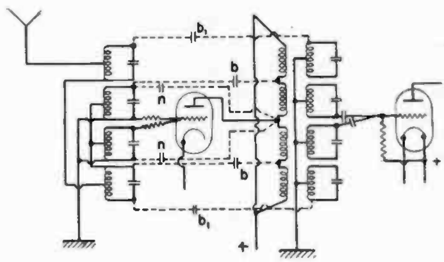

Fig. 13

with the antenna system, a multiplex transmission can be obtained very simply.

The same may be said of an antenna system used for reception, but in this case we must have many parallel open aerials or many parallel frame aerials; otherwise simultaneous excitation of all circuits by incoming waves cannot be had. This applies to intervalve filters also. For instance, if we wish to obtain an intervalve

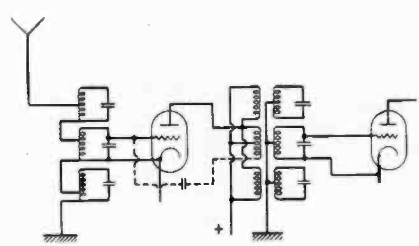

Fig. 14

filter with square-topped resonance curve or some other curve suitable for good transmission or reception, we must construct according to Figs. 10, 11, 12, 13, and 14. On these drawings *R* indicates non-inductive resistances. Intervalve filters of this kind can be constructed also to obtain resonance curves with many peaks like those of Fig. 9. This arrangement can be effected either by means of variable condensers or inductances

tuned to different wavelengths, or with fixed condensers or inductances, for instance, in superheterodyne receivers.

The same types of intervalve transformers can be utilized for amplification of a number of waves for multiplex transmission, amplification, or reception. The regenerative effect may be used and reaction coils applied (Figs. 11 and 12). These coils may be coupled with one or with all circuits, or special reaction valves and reaction circuits not connected directly to the whole system may be applied. The various possible schemes are indicated in the drawings, which are self-explanatory.

The curves obtained experimentally have been found similar to those reported in the paper by Mr. F. K. Vreeland,[2] and Figs. 6, 7, and 9 of this paper.

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Discussions on
THE RECEIVING SYSTEM FOR LONG-WAVE TRANSATLANTIC RADIO TELEGRAPHY*

Austin Bailey, S. W. Dean, and W. T. Wintringham

(At meeting of Washington, D. C., Section of the Institute, October 11, 1928)

F. P. Guthrie[1]: The most interesting points are always brought out in the discussion after the paper. I have a couple of questions I want to ask. You state you get a great improvement by going up into Maine, but there is a lot of difference between Maine and the North Pole. Could you go farther north and get greater improvement?

Austin Bailey[2]: Maybe you could. I think it is an economic question. Wire circuits cost money and power costs money, and it is a question of where you can get the best communication circuit for the least cost. If you figure you can obtain a good and more economical circuit by moving farther north, then move farther north. The transatlantic radio circuit is young yet. It is only two years old. And some further improvements may be obtained by just such means as that.

F. P. Guthrie: Does that mean that our Canadian friends have a great advantage over us always?

Austin Bailey: I think it does mean some advantage for long waves. If they are going to communicate with England, they are nearer to England, and farther away from primary sources of static.

A Member: Couldn't you get far enough north that the aurora borealis would be serious, or just what does that do to the transatlantic signals?

Austin Bailey: I have heard it twice in Cupar, Scotland, and it is a very interesting thing to hear. It gives a sort of a hissing noise. I imagine a good many people besides myself have heard it. It is a source of interference, and it may be serious, but as yet we have no data at all to indicate how serious.

A Member: During time of aurora borealis there is a very great decrease in the field strength of the signals—greatest

* Proc. I.R.E., 16, December, 1928.
[1] Radio Corporation of America, Washington, D. C.
[2] Department of Development and Research, American Telephone and Telegraph Company, New York City.

especially in the ordinary broadcast wavelengths. I have not really observed it in the longer wavelengths.

Austin Bailey: First of all, it is probable, I believe, that the aurora borealis and the variations of the magnetic field of the earth are due to a common cause. The variation in signal field strength observed in the broadcast frequency range, and much more so at higher frequencies, is probably due to magnetic field variation or to the same thing that causes both of the other things. I cannot answer what it is due to, but the fact remains that there is some correlation between these things. On the very high frequencies increase in disturbance of the magnetic field is, in general, accompanied by very low signal fields. At such times on long wavelengths you will get an increase in the daylight field strength and a decrease in the night-time field strength.

August Hund[3]: The speaker has shown us on the screen the transmission formulas due to Sommerfeld, Austin and Cohen, and Fuller, and one worked out by the Bell System and mentioned that each formula gave about the same results for the frequency band and distance in question. I wonder whether the speaker has ever tried to find out from these formulas what distance should be used for a certain frequency for the best reception at the other end. The formula lends itself very readily to such an experiment, because it is only necessary, for instance, to differentiate with respect to the frequency and solve for a maximum, or to differentiate with respect to the distance and solve for a maximum.

Austin Bailey: There is, of course, more to the problem of choosing the best frequency for a given distance than is indicated by Dr. Hund's thought. The best reception depends also upon the transmitting antenna efficiency and the static at the receiving station as shown by Figs. 1 and 2 of the paper. Furthermore, the transmission formula was derived for the particular transatlantic path under consideration, and how well it will work for any other transmission path I do not know.

August Hund: In the course of his lecture the speaker has given us a very ingenious method for getting the characteristic impedance as well as the propagation constant of his wave-antenna. The method to which I have reference measures these quantities by using two known terminating impedances at the

[3] Radio Section, Bureau of Standards, Washington, D. C.

end of the line. The reason was, if I understood it right, because the usual method, which carries on the measurement for the open-ended and shorted line, would give either unusually small or unusually large values, which would make the measurement very difficult. I just wonder whether it would not be possible to measure the characteristic impedance simply at any point by noting the potential at that point and the current through that point?

Austin Bailey: The only thing you get by doing that is the absolute value of the impedance. You cannot measure the phase angle; therefore, you cannot get the propagation constant.

August Hund: In case of a wave-antenna, we have to adjust at the transmitting end exactly to the value of the characteristic impedance. Now, I just wonder whether, for the different weather conditions, this surge impedance can be considered as constant.

Austin Bailey: As an actual matter of fact, we have made measurements over an extended period of time to determine that. The variations are remarkably small. Surface moisture and the depth to which the ground freezes do not seem to have any large effect on the antenna characteristics. The ground waves and constants are not greatly affected except by slow changes over long periods of time.

August Hund: When Dr. Austin and Dr. Cohen gave us their empirical transmission formula it worked all right for a number of years. The reason for this was that for the first series of their experiments they were working only over comparatively short distances, but as soon as Dr. Austin extended his work over considerable distances he felt the need of changing his formula in order to agree with his measurements. The reason is probably due to the fact that even in the original Sommerfeld formula we find only one exponential term. Although I do not believe in making a formula more complicated than it is already, it would seem that a formula with two exponential terms might give more reasonable values. The reason for this is because when we receive over very, very great distances sometimes a wave may go around the Great Circle one way just as well as the other way. As a matter of fact, such cases have been reported in the literature where the signal was received over each path. (Of course, in this consideration, I am not thinking of the Heaviside layer and its effect.) Now, if we should take two exponential

terms, one holding for one path and the other for the other path, it might perhaps explain why the intensity over long distances should change when only one term is used, as in the present empirical formula.

Austin Bailey: I think that there have been proposed a few transmission formulas to take into account overland and over-water transmission, but I do not believe that anyone has previously proposed your idea of transmission in two directions.

A. H. Taylor[4]: In working at the R.C.A. station at Chatham, Massachusetts, at night I noticed that the signals from Long Island could be barraged out for only a few moments at a time. I was interested in that because the variation in direction is present at night. These variations seem to be maximum around 200 miles depending somewhat on the frequency. At night here in the winter time, provided with excellent compensation there are instantaneous fluctuations of 90 deg. on New Brunswick direction and are very rapid. I have never made any measurements exactly at the frequency you are working on. Do you know what those variations are? They should be much less on transatlantic stations.

Austin Bailey: If you receive at night you run into this effect. We received at Houlton for these wave-antenna tests only in the early morning and late evening. We could not work at night because of this, and in the daytime the station was in commerical use on traffic, and so the only available times were the little pieces at the beginning of the morning about 4 to 7 A.M. and in the evening from 5 to 7 P.M. Now, as to the magnitude of this variation in the apparent direction, the signals from the mobile transmitter at a distance of about 50 miles frequently varied in direction as much as 20 deg. during the period immediately preceding sunrise. Little advantage can be taken of the directional diagram at night, but fortunately you get a fairly large signal-to-noise ratio at night and you usually can work satisfactorily. It is in the afternoon in the United States when the static comes in that the directivity is essential. You would be absolutely lost if you did not have directivity at this time of day when the signal is decreased due to the intervening shadow wall between the transmitting and receiving stations, but the static is being received mostly over an all-daylight transmission path from the opposite direction from the signal.

[4] Radio Division, Naval Research Laboratory, Bellevue, Anacostia D. C.

A. H. Taylor: We had a station at Bar Harbor, one at Long Island, one in New Jersey and at Washington. We found a progressive increase in the signal ratio especially as you went along. That is, New Jersey was distinctly better than Washington; Long Island, with inferior receiving apparatus, better than New Jersey; Chatham was distinctly better by a definite amount than New Jersey, and Bar Harbor was above everybody, not only in the signal-noise ratio, but due to the fact that the total signal intensity was tremendous up there, and you could copy from stations on much higher frequencies. During the years of the development of the Radio Corporation, it was the consensus of opinion among all of us engaged in transatlantic telegraphy that for the general New York-Washington location there was no use fooling with anything short of 12,000 meters. It simply did not go during the summer months. Are we to infer from these more recent developments with modern amplifiers, that the opinion ought to be revised? We based that opinion on the signal-noise ratio which should not be affected by amplifiers, and we also had the use of fairly directive receiving equipment. Am I to believe now that it would be possible to drop the wave for trans-oceanic telegraph and get communication in the summer time?

Austin Bailey: There is one other factor to be taken into consideration, and that is the efficiency of the transmitting antenna. Take that factor into consideration and build an antenna with Rocky Point efficiency, and you will probably get better communication service at higher frequencies even in the summer than you would on the longer wavelengths.

A. H. Taylor: If you could not go up to Maine and received it somewhere between here and New York, could you do it?

Austin Bailey: We do not have any data for locations between here and New York to answer that. On Long Island the higher frequencies are undoubtedly preferable. Of course, a directive system located as far south as New York is at great disadvantage, because a large number of storms occur in front of it, and there is no hope during these periods. At Houlton there are about 12 thunderstorms a year on the average.

A. H. Taylor: All downcoming waves have three components. In connection with the higher frequencies we have been doing some work with these components. We have fallen into the habit in our laboratory of referring to three components as the vertical, horizontal, and longitudinal thrust. The idea is generally appli-

cable to all frequencies. In order to distinguish the two horizontal components I suggest the terms "horizontal component" and "longitudinal thrust."

Austin Bailey: That is a very good suggestion. The two components, of course, in this paper, are quite intimately connected with the primary plane polarized transmitted wave, and that is the reason that we have used the two primary terms, vertical and horizontal, in connection with our work rather than vertical and longitudinal.

A. H. Taylor: By the way, do you find your night static less centered in direction than the daylight static?

Austin Bailey: Yes, more scattered, and probably partly due to the night-time directional variations already mentioned.

F. P. Guthrie: Are there any essential differences between a good antenna for telephony and a good antenna for telegraphy?

Austin Bailey: One is that the Beverage-Rice-Kellog compensation method is perfectly satisfactory for telegraphy. They are interested in balancing out disturbances at one frequency only. In telephony we have to balance out a band 3000 cycles wide, so we should have for telephony a balance which is invariable with frequency. We can turn these blind spots around against static and still maintain them over the whole telephone band range and not just at one frequency. A satisfactory antenna for telegraph receiving may not be so satisfactory for telephone receiving but not the other way around.

A. H. Taylor: Do you think that short-wave telephone transmission can ever be as good as long-wave telephone transmission?

Austin Bailey: It depends for one thing upon the power you use. If you use the same amount of power on short waves as on long waves, I should think you would get about equal reliability. Long and short waves are vulnerable from different causes. You can use small power on short waves and get away with it part of the time.

(At New York meeting of the Institute, November 7, 1928.)

Alfred N. Goldsmith[1]: This paper is a clear indication of the evolution which follows the first exciting, almost "freak" reception, (if we may use the term for reception accomplished only

[1] Chief Broadcast Engineer, Radio Corporation of America, New York City.

under especially favorable conditions,) to a steady and reliable, thoroughly planned, and capably engineered service. To listen to a paper of this sort is, therefore, not merely to receive technical information, but also to have traced before one the evolution of a portion of a new art.

In the midst of an extremely interesting discussion of a complicated subject, I hope that no one will go away with the impression that we have learned so much about the possibility of "improving" broadcasting by eliminating one side-band and suppressing the carrier that this method of transmission will be seriously proposed for ordinary broadcasting. One gets a disquieting picture of a few hundred thousand independent local oscillators working in New York City, for example, on frequencies selected by the casual listener in his operation of the receiver. This is definitely not a happy picture. The incorrect selection of the re-inserted carrier frequency in broadcasting would result in sounds even less harmonious than those which are sometimes experienced by the listener utilizing the more conventional type of receiving set.

So that it is to be hoped that optimism will not lead to the adoption, at least immediately, in broadcasting of these ingenious methods which are so thoroughly applicable in the hands of skilled operators working on a single frequency in a trans-atlantic telephone receiving station.

K. S. Van Dyke[2]: Will the authors mind stating what the order of magnitude of their ground connection impedance is, particularly with relation to the characteristic impedance of the antennas?

W. T. Wintringham[3]: Of the four antennas at Houlton, the characteristic impedances roughly average about 420 to 425 ohms. The lowest values aren't much below 400, and the highest values not much over 450.

A poor ground, for example the one that was pointed out in one of the slides as being on the top of a rocky hill, measures about 40 ohms, mostly negative reactance, whereas a good ground will measure possibly 1 or 2 ohms resistance, with between 1 and 2 ohms positive reactance.

[2] Department of Physics, Wesleyan University, Middletown, Connecticut.

[3] Department of Development and Research, American Telephone and Telegraph Company, New York City.

Haraden Pratt[4]: In these days of high-frequency technique, which is absorbing everyone's interest, it is refreshing to see such a learned discourse on the older art of low-frequency radio transmission, particularly in the telephone field, where the conditions are a little more exacting from the standpoint of the customer of the service. It is inconvenient for a telephone subscriber to be interrupted and repeat what he has to say on account of interference, and so forth, which the user of the telegraph service isn't so much aware of—a few repetitions can occur and he doesn't know about them—which fact has probably pushed the development of this receiving problem a little bit further than has been the case in the telegraph field.

The signal-to-noise ratio study has interested me particularly on account of the long statistical work which no doubt was necessary over a period of years in order to arrive at a conclusive result, and it would appear from the paper that the workers on the system are particularly fortunate in finding a combination which gave a suitable frequency from the signal-to-noise ratio standpoint, and also was within financial limits in the building of the receiving antenna system, and, fortunately, fell within the requirements from the standpoint of band width of the transmitting set.

The favorable location of receiving points in the northern part of the country, as Mr. Bailey mentioned, has been observed before, and it might be interesting to recount an experience that occurred early in the World War, when radio communications were being relied upon in case of cable interruption for military communications with Europe. It had been observed that receiving conditions in the northern part of the United States were favorable, more favorable than in the southern part, and therefore an observer was sent to Newfoundland early in 1918 to see what he could do up there in receiving the low-frequency signals from European stations, which at that time were not high in power, and which were not able to put good signals into the United States in the summertime.

That man, after he arrived at Newfoundland, found that a mistake had been made in the instructions given in regard to the equipment which he was to use, and when he unpacked his apparatus found a receiving set that had only a limited range and prevented his receiving the European stations on their usual

[4] Chief Engineer, Mackay Radio and Telegraph Company, New York City.

frequencies. But transmitting sets in those days radiated harmonics, and during the summer of 1918 this observer sent us copy from Newfoundland of signals from some of the European stations received on their harmonics, which were sent at times when the same signals could not be readily copied at the usual pointsin this country. Of course, Newfoundland had the further advant age of being much closer to the transmitting point.

The diagrams of the geological formation of the ground and the matter of ground resistance being so important I think is particularly interesting, as it shows the trend of the times in the matter of correlating the radio engineer's work with that of the geologist, the physicist, and the meteorologist, and I think it brings out a great many very interesting points in that regard.

F. H. Murray[3]: The use of Raleigh's solution of the problem of random phases in the problem under discussion leads to rather laborious computations; a shorter approximate solution is derived here. Comparison shows a close numerical agreement in some special cases.

From mathematical investigations it is known that the probability that the sum $\sum a_i \cos(V_i t + \delta_i)$ will exceed any fixed number x, the numbers V_i being incommensurable, is the same as the probability that $\sum a_i \cos\theta_i$ is greater than x, where all values of any θ_i are equally likely and these angles are independent variables. In the Dirichlet integral

$$\frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{\epsilon^{i\omega g}}{i\omega}d\omega = \begin{cases} 0, & g<0 \\ \frac{1}{2}, & g=0 \\ 1, & g>0 \end{cases}$$

let $g = \sum_{i=1}^{n} a_i \cos\theta_i - x$, then the required probability is

$$P = \left(\frac{1}{2\pi}\right)^{n+1}\int_0^{2\pi}d\theta_1\int_0^{2\pi}d\theta_2\cdots\int_0^{2\pi}d\theta_n$$

$$\int_{-\infty}^{\infty}\frac{1}{i\omega}\epsilon^{i\omega\left[\sum_r a_r\cos\theta_r - x\right]}d\omega$$

Interchanging the order of integration and letting $a_i = a$, we have

$$P = \frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{1}{i\omega}\epsilon^{-i\omega x}J_0(a\omega)^n d\omega$$

where J_0 is the Bessel function of order 0.

If N is the total number of possible sources of terms $a\cos\theta_i$, p the probability that any one source will contribute its term, and the same for all, the probability that enough terms are present and have the proper phases to make $\sum a_i \cos\theta_i > x$ is equal to

$$\overline{P}(x) = \sum_{n=0}^{N} \binom{N}{n} p^n (1-p)^{N-n} \cdot \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{1}{i\omega}\epsilon^{-i\omega x} J_0(a\omega)^n d\omega$$

$$= \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{\epsilon^{-i\omega x}}{i\omega}[1-p(1-J_0)]^N d\omega.$$

To find an approximate value for $\overline{P}(x)$, observe that

$$[(1-p)+pJ_0]^N$$

has its maximum value (for real ω) at $\omega=0$, and decreases rapidly for large $|\omega|$. Hence only the values of ω near $\omega=0$ are of importance in the integral $\overline{P}(x)$. Writing

$$\log\,[1-p(1-J_0)] = -p(1-J_0) - \frac{p^2}{2}(1-J_0)^2 - \frac{p^3}{3}(1-J_0)^3 \cdots$$

$$1-J_0(a\omega) = \frac{(a\omega)^2}{4} - \frac{a^4\omega^4}{64} + \frac{a^6\omega^6}{2304} - \frac{a^8\omega^8}{2^8(4!)^2} \cdots$$

we have finally, for $a=1$, $Np=A$,

$$N\log\,[1-p(1-J_0)] = -\frac{A}{4}\omega^2 + Aa_1\omega^4 + Aa_2\omega^6 Aa_3\omega^8 + \cdots$$

$$a_1 = \frac{1}{2^6} - \frac{p}{2^5},$$

$$a_2 = \frac{-1}{9\cdot 2^8} + \frac{p}{2^8} - \frac{p^2}{3\cdot 2^6}$$

$$a_3 = \left[\frac{1}{(4!)^2} - \frac{17p}{288} + \frac{p^2(1-p)}{4}\right]\cdot\frac{1}{2^8}$$

Consequently

$$\epsilon^{N\log\,[1-p(1-J_0)]}$$

$$= \epsilon^{-A\omega^2/4}\left[1 + Aa_1\omega^4 + Aa_2\omega^6 + \left(Aa_3 + \frac{A^2a_1^2}{2}\right)\omega^8\right] + \cdots$$

If $z = i\omega$, the required probability becomes

$$\overline{P}(x)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{\epsilon^{-zx}}{z}\epsilon^{(Az^2/4)}d\omega$$

$$+\frac{1}{2\pi}\int_{-\infty}^{\infty}\epsilon^{-zx+(Az^2/4)}\left[Aa_1z^3-Aa_2z^5+\left(Aa_3+\frac{A^2a_1^2}{2}\right)z^7\right]d\omega.$$

If $B=A/2$, $erf\ (x)=2/\sqrt{\pi}\int_0^x \epsilon^{-t^2}dt$, this becomes

$$\overline{P}(x)=\frac{1}{2}\left[1-erf\left(\frac{x}{\sqrt{A}}\right)\right]-\frac{\epsilon^{-x^2/A}}{\sqrt{\pi A}}\left[Aa_1\left(\frac{3x}{B^2}-\frac{x^3}{B^3}\right)\right.$$

$$-Aa_2\left(\frac{-15x}{B^3}+\frac{10x^3}{B^4}-\frac{x^5}{B^5}\right)$$

$$\left.+\left(Aa_3+\frac{A^2a_1^2}{2}\right)\left(\frac{105x}{B^4}-\frac{105x^3}{B^5}+\frac{21x^5}{B^6}-\frac{x^7}{B^7}\right)\right]+\cdots$$

In the case $N=100$, $p=0.15$, the first term of this sum gives the correct value within a few per cent. if $x=5$.

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Discussion on
DETECTION WITH THE FOUR-ELECTRODE TUBE*

(J. R. Nelson)

F. B. Llewellyn[1]: The relations given in Mr. Nelson's valuable paper have suggested several interesting points in connection with detectors in general and screen-grid detectors in particular. Equation (23) in Mr. Nelson's paper,[2] or (31) and (32) in my own paper, give the expression for detected current. This expression for the case where two sine waves of voltage

$$A \cos ht + B \cos kt$$

are applied to the grid gives for the component of plate current of frequency $(h-k)$ the following expression:

$$i_{(h-k)} = \frac{1}{2}\left(\frac{r_p}{r_p + z_{(h-k)}}\right)$$

$$\left\{\frac{\partial g_m}{\partial E_g} - \left(\frac{\mu z_h}{r_p + z_h} + \frac{\mu \bar{z}_k}{r_p + \bar{z}_k}\right)\frac{\partial g_m}{\partial E_p} - \frac{g_m{}^2 z_h \bar{z}_k}{(r_p + z_h)(r_p + \bar{z}_k)}\frac{\partial r_p}{\partial E_p}\right\} AB\cos(h-k)t.$$

It is the nearly invariable practice in detector design to make $z_h = z_k = 0$. In that case the above expression reduces to the simple relation,

$$i_{(h-k)} = \frac{1}{2}\left(\frac{r_p}{r_p + z_{(h-k)}}\right)\frac{\partial g_m}{\partial E_g} AB \cos (h-k)t.$$

Moreover, since the static characteristic for $I_p - E_g$ with a fixed value of E_p may be represented over a considerable range by an expression of the form

$$I_p = KE_g{}^n$$

we have

$$\frac{\partial g_m}{\partial E_g} = \frac{n-1}{nI_p} g_m{}^2$$

or, when $n = 2$

$$\frac{\partial g_m}{\partial E_g} = \frac{g_m{}^2}{2I_p}$$

* Proc. I. R. E., **16**, 822; June, 1928.

[1] Bell Telephone Laboratories, New York City.

[2] F. B. Llewellyn, "Operation of Thermionic Vacuum Tube Circuits," *Bell System Tech. Jour.*, July, 1926.

which is convenient for rapid approximations. When a more accurate evaluation is desired, the dynamic method suggested by Mr. Nelson is a simple and reliable one provided small values of input a.c. voltage only are employed.

Since, as shown above, detection depends upon the coefficient $\frac{\partial g_m}{\partial E_g}$ which is equivalent to $\frac{\partial}{\partial E_g}\left(\frac{\mu}{r_p}\right)$, and since for the screen-grid tube μ varies considerably in the operating region, it is evident that detection with that type of tube is accomplished primarily by μ variation. This is in striking contrast to the operation of the ordinary three-element tube where μ is fairly constant, and the greater portion of the detection arises from variation of r_p.

J. R. Nelson[3]: Mr. Llewellyn points out that in using the dynamic method suggested in my report only small input a.c. voltages should be used. This is in general true, and the more sensitive the detector the smaller the a.c. input voltage should be. A screen-grid tube, however, is an exception to the general case as large a.c. input voltages may be applied to the grid of the tube and values of $\partial g_m/\partial e_g$ found will check the values obtained with the smaller a.c. input voltages. This is due to the fact as pointed out in the paper that the variation of G_m with regard to E_g is practically constant in the range studied.

The method suggested by Mr. Llewellyn is a very convenient one for comparing different tubes as bias detectors or finding the best operating point of a tube. The values of G_m and I_p at the operating point are easily found.

Mr. Llewellyn in a letter to the author pointed out an error in (22) and following equations so that ${}_{(h-k)}a_2$ in (23) to (29) should read

$$
{}_{h-k}a_2=\frac{r_p}{2}\,\frac{1}{r_p+z_{h-k}}\left\{\frac{\partial g_m}{\partial e_g}-\left[\frac{\mu\bar{z}_k}{r_p+\bar{z}_k}+\frac{\mu z_h}{r_p+z_h}\right]\frac{\partial g_m}{\partial E_p}\right.
\left.-\frac{g_m{}^2 z_h\bar{z}_k}{(r_p+z_h)(r_p+\bar{z}_k)}\,\frac{\partial r_p}{\partial E_p}\right\}.
$$

Instead of

$$
{}_{h-k}a_2=\frac{1}{2}\,\frac{r_p}{r_p+{}_{h-k}z}\left\{\frac{\partial g_m}{\partial E_g}-\frac{2\mu_k\bar{z}_1}{r_p+{}_k\bar{z}_1}\,\frac{\partial g_m}{\partial E_p}+\frac{g_m{}^2{}_h z_1{}_k\bar{z}_1}{(r_p+{}_h z_1)(r_p+{}_k\bar{z}_1)}\,\frac{\partial r_p}{\partial E_p}\right\}.
$$

This, however, does not affect the results or conclusions as (29) and following equations are not changed.

[3] E. T. Cunningham, Inc., New York City.

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BOOK REVIEW

A Bibliography of Electrical Literature. Serial No. 62; Publications from the Massachusetts Institute of Technology. 62 pages, paper bound; price 50c.

Contains publication data and outlines scope of the material included in publications and bulletins devoted to electrical information. It is useful as a guide for either the systematic or desultory study of published electrical engineering contributions from both American and foreign sources.

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MONTHLY LIST OF REFERENCES TO CURRENT RADIO LITERATURE*

THIS is a monthly list of references prepared by the Radio Laboratory of the Bureau of Standards and is intended to cover the more important papers of interest to professional radio engineers which have recently appeared in periodicals, books, etc. The number at the left of each reference classifies the reference by subject, in accordance with the scheme presented in "A Decimal Classification of Radio Subjects—An Extension of the Dewey System," Bureau of Standards Circular No. 138, a copy of which may be obtained for 10 cents from the Superintendent of Documents, Government Printing Office, Washington, D. C. The articles listed below are not obtainable from the Bureau of Standards. The various periodicals can be consulted at large public libraries.

R100. Radio Principles

R007.1 Hooper, S. C. Considerations affecting the licensing of high frequency stations. Proc. I.R.E., 16, 1240-51; September, 1928.
(Discussion based on study while with the Federal Radio Commission.)

R113 Edwards, S. W., and Brown, J. E. The use of radio field intensities as a means of rating the outputs of radio transmitters. Proc. I.R.E., 16, 1173–93; September, 1928.
(A method described by which outputs of radio transmitting sets can be regulated by federal authority in terms of measured radio field intensities instead of watts in the transmitting set or antenna circuit. Work done on broadcast range only. Field intensity contour maps given for several stations.)

R113 Jansky, C. M. Jr. Some studies of radio broadcast coverage in the middle West. Proc. I.R.E., 16, 1356–67; October, 1928.
(Statistical study based on reports to station WBBM.)

R113.2 Austin, L. W. Long-wave radio receiving measurements at the Bureau of Standards in 1927. Proc. I.R.E., 16, 1252–57; September, 1928.
(Curves and tables give daylight signal intensities of a number of stations and strength of atmospheric disturbances.)

R113.4 Breit, G.; Tuve, M. A.; Dahl, O. Effective heights of the Kennelly-Heaviside layer in December, 1927 and January, 1928. Proc. I.R.E., 16, 1236–39; September, 1928.
(Report on results of effective heights of Kennelly-Heaviside layer obtained Dec. 19, 1927 to Jan. 16, 1928 by the reflection method.)

R113.6 Hoag, J. B. and Andrew, V. J. A study of short-time multiple signals. Proc. I.R.E., 16, 1368–74; October, 1928.
(An investigation of signals which may have travelled one or more times around the earth. Shows reflections of signals from region other than Heaviside layer.)

* Original manuscript received by the Institute, November 14, 1928.

R125.6 Turlyghin, S. J. and Ponomareff, M. J. Zusammengesetze Rahmenantennen. (Combination of coil antennas). *Zeitschrift für Physik*, 9, 356–64; 1928.

(Theoretical investigation of coil antennas and coil combinations, and coil antennas with reflectors.)

R125.6 Walmsley, T. Polar diagrams due to plane aerial reflector systems. *Experimental Wireless* (London), 5, 575–77; October, 1928.

(Derivation of formulas by means of which the polar diagram in any vertical plane can be plotted. It is shown that the field behind the reflector is of considerable strength.)

R130 Crossley, A. and Page, R. M. A new method for determining efficiency of vacuum tube circuits. Proc. I.R.E., 16, 1375–83; October, 1928.

(Method described for determining efficiency of vacuum-tube circuits for high and low frequencies by application of surface pyrometer indicating temperature of glass walls of tube.)

R131 Reed, M. The application of alignment charts to valve characteristics. *Experimental Wireless* (London) 5, 571–74; October, 1928.

(The theory of alignment charts is given and applied to the tube equation for the anode and grid voltages and the plate current.)

R132 von Ardenne, M. The final or power stage of amplifiers. *Experimental Wireless* (London), 5, 556–64; Oct., 1928.

(A discussion of the performance of the amplifier stage energizing a loudspeaker. The circuit is treated by means of the dynamic characteristic.)

R132 Medlam, W. B. Effect of anode-grid capacity in detector and low frequency amplifiers. *Experimental Wireless* (London), 5, 545–55; October, 1928.

(An analytical treatment of the effect of the internal tube capacity for detector and low frequency amplifier circuits.)

R132 Watanabe, Y. Über den rückgekoppelten Verstärker. (On feedback amplifiers). *Zeitschrift für Hochfrequenztechnik*, 32, 77–83; September, 1928.

(Equations for the amplification of amplifiers with electrostatic and magnetic feedback.)

R133 Grechowa, M. Zur Frage der Erzeugung kurzer elektromagnetischer Wellen. (On the production of short electro-magnetic waves). *Physikalische Zeitschrift*, 29, 726–29; October 15, 1928.

(Based on an equation by Abraham; the case of the Barkhausen and the Gill and Morrell oscillations is studied with respect to their frequency.)

R133 Pfitzer, W. Die Selbsterregungsbedingungen bei Rückkopplungs- Röhrensendern für sehr kurze Wellen. (The condition for self excitation for short waves of tube generators with feedback) *Electrische-Nachrichten Technik*, 5, 348–69; September, 1928.

(The oscillations for very short waves are investigated by taking into account the ground capacity and the interelectrode effects. It is shown that the circuit acts like a voltage divider. The feedback conditions can than be expressed by simple equations which give expressions for the natural oscillations.)

R134 Terman, F. E. Some principles of grid-leak grid-condenser detection. Proc. I.R.E., 16, 1384–97; October, 1928.

(Bases discussion on equivalent circuits, measures detection factors.)

R145.3 Wheeler, H. A. Simple inductance formulas for radio coils. Proc. I.R.E., 16, 1398–1400; October, 1928.

(Two simple formulas presented which are patterned after an empirical formula derived by Prof. L. A. Hazeltine for inductance of simple types of radio-frequency coils.)

R200. Radio Measurements and Standardization

R201.2 Eisner, F. Über punktformige Aufnahme von Wechselstromkurven, insbesondere bei hoher Frequenz. (On the point by point method for tracing a.c. curves particularly at high frequency). *Archiv. für Elektrotechnik*, 20, 473–502; Sept. 17, 1928.

(A three-electrode tube method is described for tracing wave shapes by the point to point method. The method seems good up to about 10 kc although results have been obtained up to 150 kc.)

R210 Westman, H. P. Frequency stability by magnetostriction oscillators. *QST*, 12, 21–26; November, 1928.

(Comparison of oscillators and calibration of frequency meters by magnetostriction oscillators.)

R220 Graham, V. M. A gang capacitor testing device. Proc. I.R.E., 16, 1401–03; October, 1928.

(Description of testing of gang condensers.)

R250 Coursey, P. R. On the application of condensers to the measurement of large radio frequency currents. *Experimental Wireless* (London), 5, 565–71; October, 1928.

(The methods for measuring large radio-frequency currents are discussed and the method with two condensers in parallel is described in detail.)

R251.2 Colebrook, F. M. and Wilmotte, R. M. The design of non-contact thermo-junction ammeters. *Experimental Wireless* (London), 5, 538–44; October, 1928.

(Contact and non-contact types of thermo-junction a.c. ammeters are compared. General principles are given of the designing of the non-contact type. Description of two designs of non-contact types embodying these principles with details as to performance. An account of a particular application as a known source of radio frequency voltage is given.)

R300. Radio Apparatus and Equipment

R326 Szekely, A. Über die einem Empfanger durch Erdung zugefuhrte Energie II. (On a receiving set, energy for which comes from the gound—II.) *Zeits. für Hochfrequenztechnik*, 32, 83—86; September, 1928.

(The author finds that a coil antenna which has in addition a vertical lead-in to ground gives a larger current reading. The increase is due to the induction of the field on the vertical lead and is not due to the ground.)

R342 Rukop, H. Die elektrischen Eigenschaften der Rundfunksender-Vorverstarker im Hinblick auf ihre akustischen Qualities. (On the electrical properties of broadcast transmitter amplifiers with

regard to their acoustic qualities). *Zeits. für Hochfrequenztechnik*, **32**, 86—93; September, 1928.

(Final paper of articles which appeared in this periodical **32**, 18, 1928 and **32**, 65, 1928. Deals with the frequency-amplitude characteristics of the amplifier.)

R342.15 Diamond, H. and Stowell, E. Z. Note on radio-frequency transformer theory. Proc. I.R.E., **16**, 1194–1202; September, 1928.

(General equations worked out which include the effect of the distributed capacity coupling existing between transformer windings.)

R382 Rucklin, R. Ein experimenteller Beitrag zum Spulenproblem. (An experimental contribution on the coil problem). *Archiv für Elektrotechnik*, **20**, 507–532; September 17, 1928.

(Experimental and theoretical investigation of single layer and pancake coils with respect to the critical frequency and current and voltage distribution. The theory includes also the contributions due to Rudenberg, Wagner, Boehm, von Steidingen, Rogowski, and Dreyfuss.)

R385.3 Schulgin, W. M. Der Wehnelt-Unterbrecher als Generator elektromagnetischer Schwingungen. (The Wehnelt interruptor as generator of electromagnetic oscillations.) *Physikalische Zeitschrift*, **29**, 724–26; October 15, 1928.

(Across a Wehnelt interruptor (platinum-lead) a resonator is connected and a voltage from a direct-current source impressed across the interruptor (platinum forms the negative pole). High-frequency oscillations are produced in the resonator circuit as in the arc generator.)

R385.5 Hartmann, C. A. Neuere Untersuchungen an Kohlmikrophonen. (New investigations on carbon microphones.) *Elektrische-Nachrichten Technik*, **5**, 344–47; September, 1928.

(Methods for testing microphones.)

R388 Sommerfeld, E. Über ein Kathodenoszillographen höher Spannungs-empfindlichkeit. (On a cathode-ray oscillograph of high voltage sensitivity.) *Archiv für Elektrotechnik*, **20**, 607–618; September 17, 1928.

(A cathode-ray oscillograph with accelerated grid and inside photographic arrangement with a sensitivity of 0.1 cm per volt is described.)

R388 Rogowski, W., Sommerfeld, E., and Wolman, W. Empfindlicher Glühcathodenoszillograph für Innenaufnahmen in einem Vorvakuum. (Sensitive cathode-ray oscillograph for photos inside the tube under a vacuum.) *Archiv für Elektrotechnik*, **20**, 619–24; September 17, 1928.

(The effect of the acceleration grid is brought out by several oscillograms. It is shown that slow electrons only slightly affect the photographic plate which is inside the tube and an increase of the speed of the electrons by fast transients does not help much. The slow moving electrons are therefore accelerated by a grid before falling in the plate. If an accelerating grid is not used, it is better to photograph the fluorescence with a camera outside the tube.)

R500. Applications of Radio

R521 Pratt, H. and Diamond, H. Receiving sets for aircraft beacon and telephony. Bureau of Standards Journal of Research, October, 1928. Research Paper No. 19. Reprint copies obtainable for 15 cents from the Supt. of Documents, Government Printing Office, Washington, D. C.

(Design details for three receiving sets of slightly different type developed for aircraft beacon and telephony. Brief discussion of the results of practical flight tests.)

R526.1 Dunmore, F. W. Design of tuned reed course indicators for aircraft radiobeacon. Bureau of Standards Journal of Research, November, 1928. Research Paper 28. Reprint copies obtainable for 5 cents from the Supt. of Documents, Government Printing Office, Washington, D. C.

(Description of tuned reed indicators for aircraft radiobeacon, visual system.)

R526.1 Shangraw, C. C. Radiobeacons for transpacific flights. Proc I.R.E., **16**, 1203–35; September, 1928.

(Description of equi-signal radiobeacon system developed by the Air Corps and Signal Corps Aircraft Radio Labs. Application of these radiobeacons in the recent trans-pacific flights.)

R536 Jakosky, J. J. Electrical prospecting. Proc. I.R.E., **16**, 1305–55; October, 1928.

(Electrical geophysical methods for locating minerals.)

R582 Picture telegraphy. Post Office Engrs. *Jnl.* (London), **21**, 191–99; October, 1928.

(Résumé of various systems of picture telegraphy.)

R600. Radio Stations; Equipment, Operation and Management

R610 Pession, G. and Montefinale, G. Radiotelegraphic center at Rome (San Paolo). Proc. I.R.E., **16**, 1404–21; October, 1928.

(Description of station San Paolo including new short-wave transmitting set.)

R800. Non-Radio Subjects

534 Trendelenburg, F. Zusammenfassenden Bericht: Über neuere akustische und insbesondere elektroakustische Arbeiten. (Summary report: On new acoustic and especially electrical acoustic papers.) *Zeits. für Hochfrequenztechnik*, **32**, 94–99; September 1928.

(In this continuation of a series of papers the acoustic field in space is discussed. The treatment considers reverberation such as originally given by W. C. Sabine and lately by F. R. Watson.)

534 Die Tonerzeugung durch Spitzen an hohen Wechselpotential und ihre Verwendung als membranloser Lautsprecher. (The sound production by means of needle gaps and high alternating potential and its application to a loudspeaker without a diaphragm.) *Naturwissenschaft*, **16**, 795–96; October 19, 1928.

(A method is described where by means of a needle gap and a high voltage across it, sounds are produced. This principle is then applied to a new type of a loudspeaker.

534.3 Harrington, E. A. The vibration of tuning forks. *Jnl.* Optical Soc. and Rev. of Scientific Instruments, **17**, 224–39; September, 1928.

(Theoretical and experimental study of electrically driven tuning forks and bars. Results: The deflection of the prongs approximately equal to equivalent length and only about 3.5 per cent of the total energy converted into sound.)

534.83 Service, J. A. Radio acoustic position finding in hydrography. *Journal* A.I.E.E., **47**, pp. 670–74; September, 1928.

(In this method the sound of a bomb alongside the ship whose position is to be determined affects a microphone at the shore and by means of it sends out a radio signal

which is recorded on the same chronograph as the report of the bomb on the ship. The time interval between sound report and radio signal gives a means for calculating the distance to the shore. In addition, a device for quickly plotting the field sheet is described.)

537.65 Skellet, A. M. Visual method for studying modes of vibration of quartz plates. *Jnl.* Optical Soc. of America and Rev. of Scientific Instruments, 17, 308–17; October, 1928.

(Experimental study of the different modes of resonator frequencies of quartz plates. The glow discharge method of Giebe and Scheibe is used.)

538 Masiyama, Y. On the magnetostriction of a single crystal of nickel. Science Reports of Tohoku University, Japan, 17, 945–61; August, 1928.

(Longitudinal and transverse effects due to magnetostriction were studied in a crystal of nickel whose shape was that of an oblate ellipsoid. When the ellipsoid was in different positions of a magnetic field, the longitudinal effect produces a contraction. The transverse effect is the reverse.)

Proceedings of the Institute of Radio Engineers
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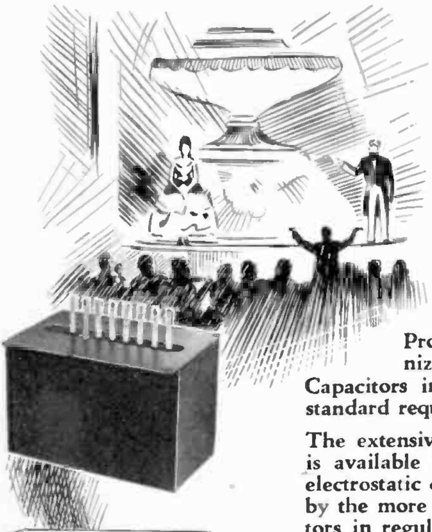

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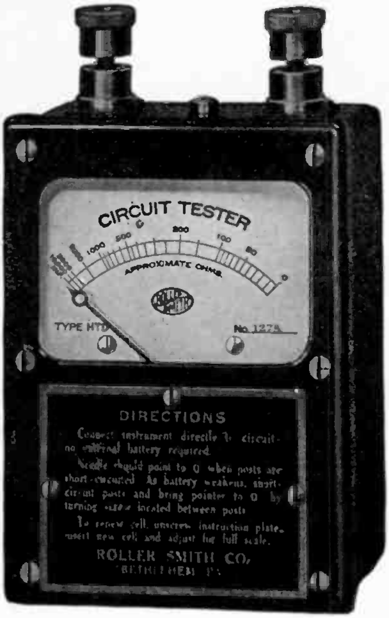

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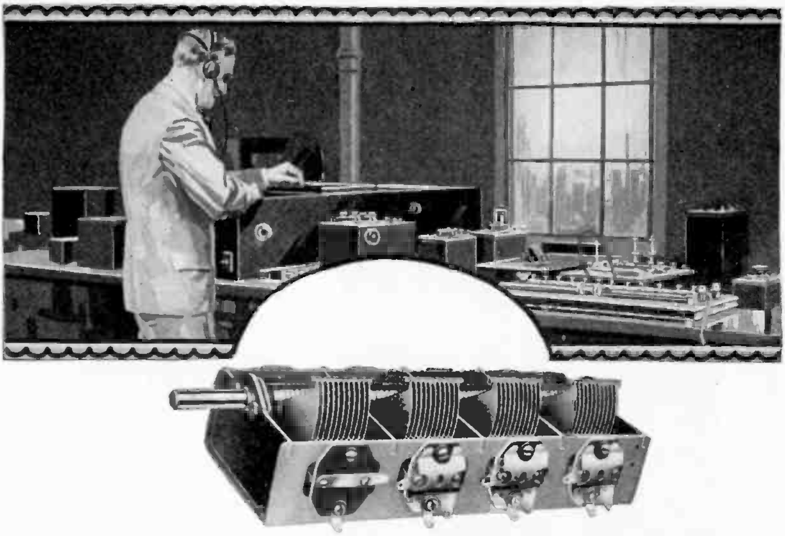

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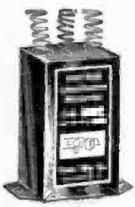

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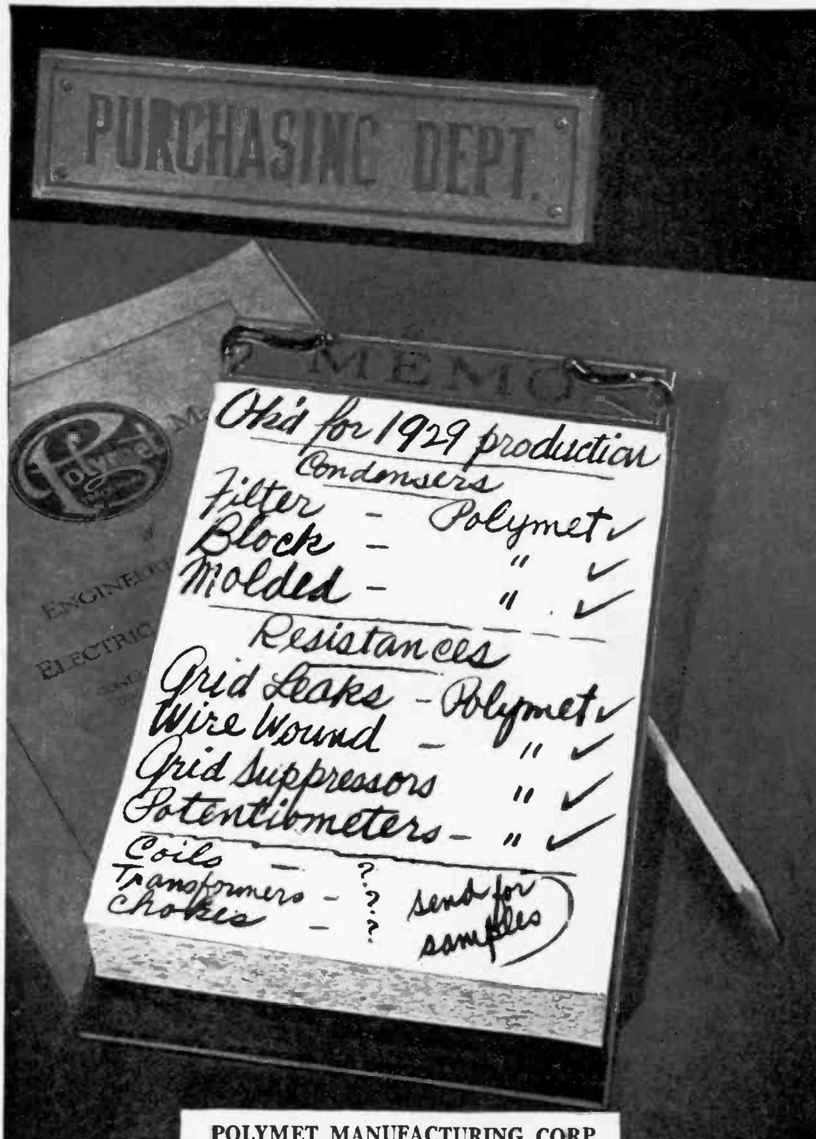
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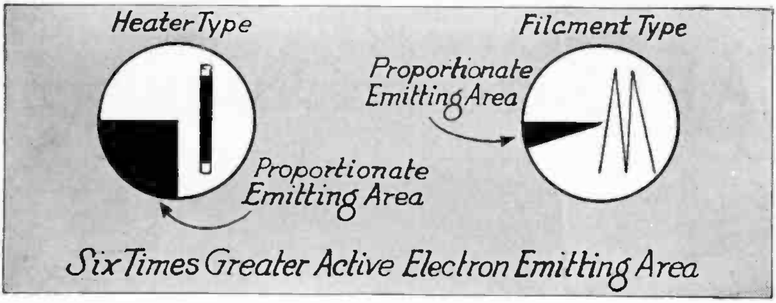

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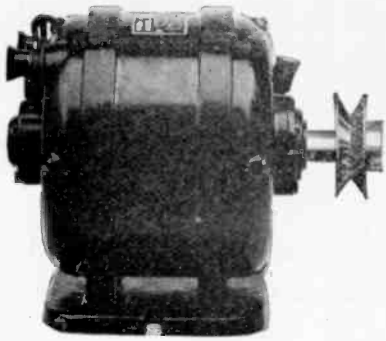

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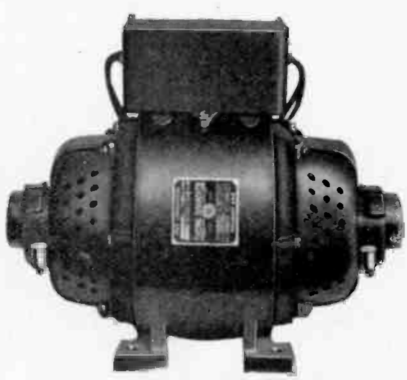

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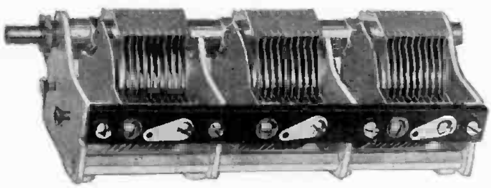

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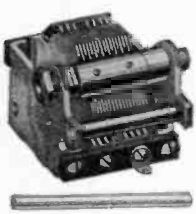

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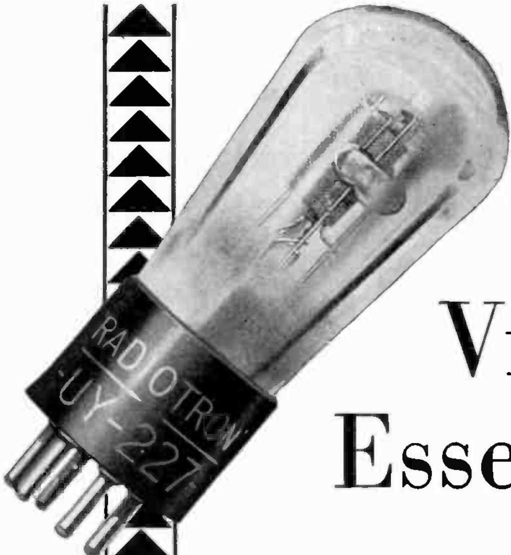

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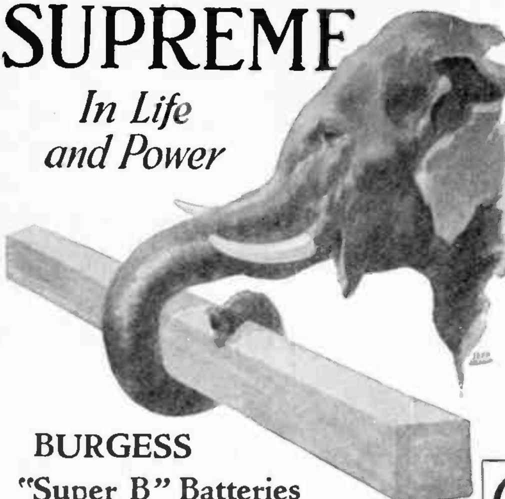

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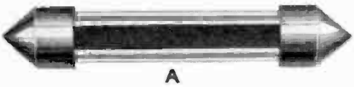
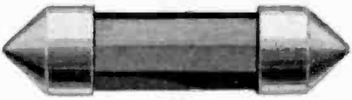


A

Type A for grid leaks and light power purposes. Will dissipate ½ watt safely.

W

Types W and X for greater power dissipation.

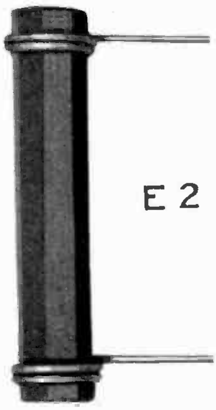


X

All types furnished in any resistance value desired.

In use continuously for a number of years by the largest manufacturers.

Types E2 and D2 furnished with wire leads soldered to coppered ends, are for soldering permanently into position in apparatus where they are to be used.



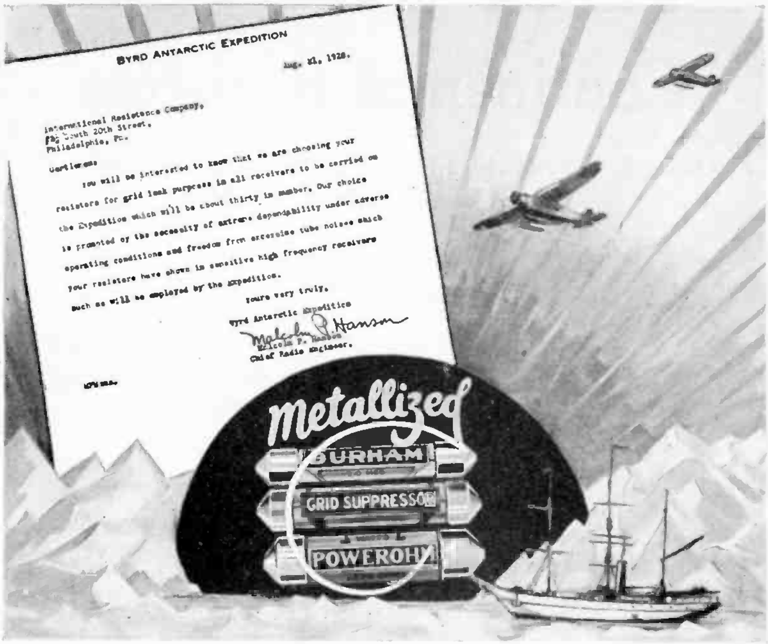
E 2

D 2

Samples for test sent on receipt of specifications.

CONTINENTAL CARBON INC.

WEST PARK, CLEVELAND, OHIO



On Commander Byrd's Antarctic Expedition Only DURHAMS are Used!

—another tribute to the DURHAM Metallized principle!—another tribute to the extreme care with which DURHAM Resistors, Powerohms and Suppressors are made!—another tribute to DURHAM accuracy and utter dependability!—read the above letter from Chief Radio Engineer Malcolm P. Hanson of the Byrd Antartic Expedition. In effect he says "We are using DURHAMS exclusively because past experience has taught us that they can be relied upon for perfect performance under even the most adverse conditions." DURHAM Resistances are available for every practical resistance purpose in radio and television work from 250 ohms to 100 Megohms and in ratings for all limited power purposes. Used in leading radio laboratories, endorsed by leading engineers and sold by leading jobbers and dealers. Descriptive literature on the entire line of DURHAM products will be gladly sent upon request.

DURHAM METALLIZED

RESISTORS & POWEROHMS

International Resistance Company, 2006 Chestnut Street, Philadelphia, Pa.

Perform that "Adenoid Operation" on Your set!

TAKE out the "adenoids", those inferior transformers which make your set sound as if it were afflicted with a bad case of adenoids . . . then put in their place, the standard of excellence in Audio Transformers—AmerTran De Luxe.

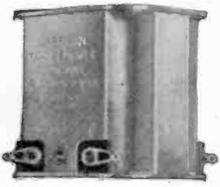
Ever hear a child talk before and after an adenoid operation? Well, if you have, you will appreciate the difference AmerTran transformers will make in any set.

AmerTran products are built exclusively for the purpose of achieving realism in tone. It cannot be done cheaply, or haphazardly. AmerTran's 30 odd radio products all play their definite part in producing the finest tone known to Radio.

Why not perform that "adenoid operation" today? See your dealer or write to us. Ask for Bulletin No. 1084.

AmerTran De Luxe—1st stage turn ratio, 3. 2nd stage turn ratio, 4.

Price each $10.00



AMERTRAN

TRADE MARK REG. U.S. PAT. OFF.

AMERICAN TRANSFORMER COMPANY

Builders of Transformers for more than 29 years

80 EMMET ST. NEWARK, N. J.

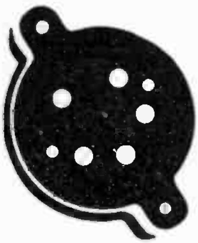
"a big improvement over what we had been using . . . "

What do you want laminated bakelite to do? What electrical, mechanical and physical properties are required for better fabrication and performance in your particular case?

Every problem is a different one. Each specific use requires its own formula. Put it up to our Service Engineering Department to determine the formula which best meets your requirements right down the line—hardness, tensile strength, thickness, appearance, dielectric strength, machining qualities, weight, cost, etc.

Our files are replete with the data and formulae on thousands of problems in laminated bakelite. The solution to your difficulties is probably among them. Put it up to us to find out.

PHENOLITE
Reg. U.S. Pat. Off.
Laminated BAKELITE
SHEETS : RODS : TUBES : SPECIAL SHAPES



. . . it punches cold

One of America's largest radio manufacturers required a laminated bakelite which would punch cold without "cold flow" yet still retain its high dielectric strength and non-hydroscopic property. Our Service Engineering Department worked months on this problem—and solved it to the entire satisfaction of our customer. Perhaps we can do an equally valuable service for you in the laboratory "where known requirements meet known performance." Call us at any time.

NATIONAL VULCANIZED FIBRE CO.
WILMINGTON, DEL.
Offices in Principal Cities

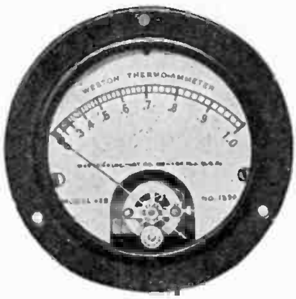
When writing to advertisers mention of the PROCEEDINGS *will be mutually helpful.*

Thermo - Couple Type Instruments - *Model* 425

INSTRUMENTS of this type, originated and developed by the Weston Company, are universally employed for measuring both high and low frequency currents. Their use has extended with the wide application of radio frequency into a great number of fields of experimental engineering and commercial activity. Incomparable in their refinements of mechanical and electrical design and unusually accurate and dependable in performance for such small instruments, the Weston Miniature Meters—Thermo-Couple types as well as A.C. and D.C. models—are everywhere accepted as the highest standards for radio testing service.

Thermo-Couple Types

Made as Thermo-Ammeters, Thermo-Milliammeters, and Thermo-Galvanometers or Current Squared Meters



For Panel Mounting

Flush Type—2" and 3¼" diameter. Furnished in metal or bakelite cases. Portable mounting bases also supplied.

The Weston Thermo-Couple Type Ammeter is furnished in ranges from one to 20 amperes having a safe overload capacity of 50%. It solves perfectly the problem of measuring high frequency currents such as are imparted to the antennae. Equally accurate for low frequency measurements and gives satisfactory service for D.C. measurements as well as A.C.

Milliammeters are furnished in three sizes—125, 250 and 500 ma. They give definite assurance of the output and accurate readings after hours of constant service. Extra large overloads will not burn out these meters. They are ideal for short wave transmission as they have a very low internal electrostatic capacity. For this reason they give the true value of the current in the circuit and do not disturb the constants in a transmitter.

Write for Circular J.

WESTON ELECTRICAL INSTRUMENT CORPORATION
589 Frelinghuysen Avenue Newark, N. J.

WESTON
RADIO
INSTRUMENTS

Rising to the needs of a Great Industry

The requirements of the modern radio, are more and more exacting.

As receiving sets improve, coils must be more accurate to keep pace with the fine calibrations of the expert radio engineer.

This is why the world's most successful radio manufacturers turn to Dudlo for their supply of coils for every part of their instruments.

The Coil's the thing! that makes Radio

Dudlo coils are not only wound accurately, but every part and material from the core to the outside wrapping is selected and applied with skill—a skill which could only come from an organization trained over many years of making millions upon millions of coils for every electrical purpose.

No radio unit is any better than its coil and no coil is any better than the wire in its windings. Dudlo draws and insulates the wire and controls every part and process from the copper rod to the finished coil. A complete service to the radio and electrical industries.

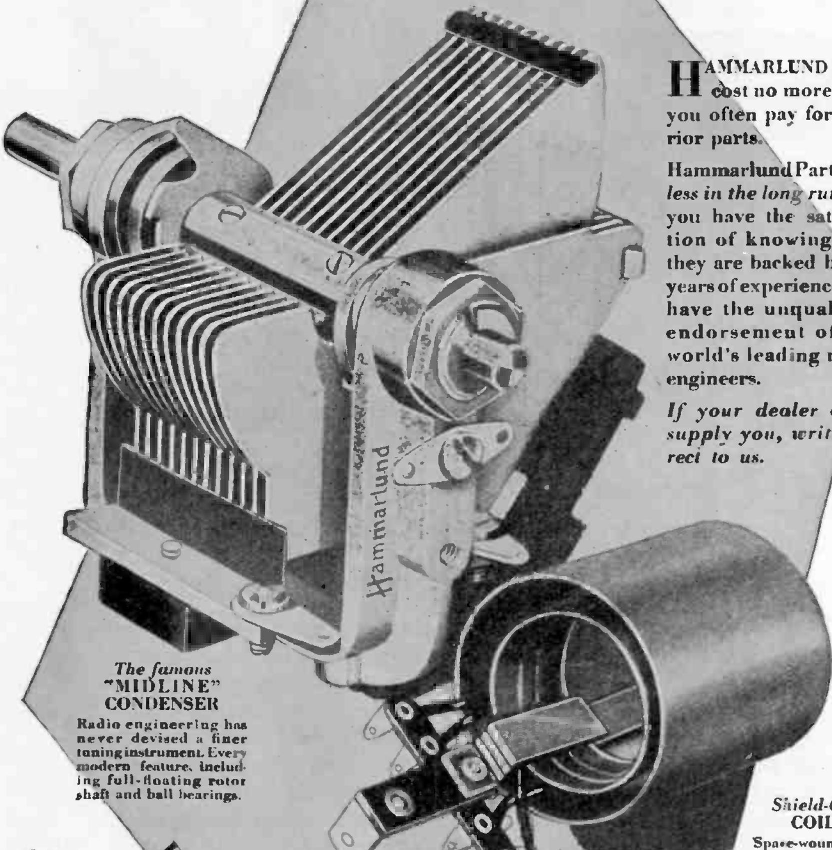
DUDLO MANUFACTURING CO., FORT WAYNE, INDIANA

Division of the General Cable Corporation

56 Earl Street NEWARK, N. J.	105 West Adams St. CHICAGO, ILL.	4143 Bingham Ave. ST. LOUIS, MO.	274 Brannan St. SAN FRANCISCO, CALIF.

If it's "HAMMARLUND"

It's BETTER!



HAMMARLUND Parts cost no more than you often pay for inferior parts.

Hammarlund Parts *cost less in the long run* and you have the satisfaction of knowing that they are backed by 17 years of experience and have the unqualified endorsement of the world's leading radio engineers.

If your dealer can't supply you, write direct to us.

The famous
"MIDLINE" CONDENSER

Radio engineering has never devised a finer tuning instrument. Every modern feature, including full-floating rotor shaft and ball bearings.

Shield-Grid
COILS

Space-wound, 2" in diameter. High impedance primary with three taps. Specially designed for shield-grid tubes.

—P. E.—

We are interested in Hammarlund

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For Better Radio

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PRECISION

PRODUCTS

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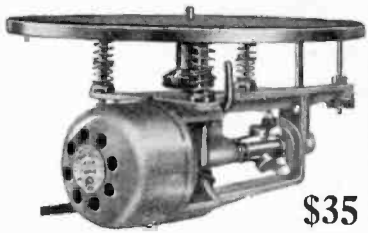
PACENT
Phonomotor



$35

The Finest Electric Power Plant for Phonographs Made

Ideal for converting the old-fashioned hand-wound phonograph to electric operation or for use in portables

THE Pacent Phonomotor is achieving nation-wide prominence as the finest and most silent electric phonograph motor that money can buy. It is of squirrel-cage construction —induction type—and absolutely eliminates brushes and sparking. Spring suspension turntable, felt cone friction drive, of shock-absorbing design throughout, it is 100% insulated against noise. Oversized burnished ball bearings, readily accessible lubrication system, it is scientifically engineered to be the most efficient and longest wearing electric phonograph motor on the market.

Ask your dealer or write for complete information, prices, discounts, etc.

PACENT ELECTRIC CO., Inc., 91 Seventh Ave., New York City

Pioneers in Radio and Electric Reproduction for Over 20 Years

Manufacturing Licensee for Great Britain and Ireland, Igranic Electric Co., Ltd., Bedford, England

The Pyrohm is Built
to Carry the Load!

AEROVOX Fixed and Tapped Vitreous Enamelled Pyrohm Resistors are made in a wide range of resistance values and wattage ratings to suit every power supply requirement. They are built to the same high standards as Aerovox Mica Condensers, Socket Power Condensers and Filter Condenser Blocks.

The August issue of the Aerovox Research Worker contains an interesting and instructive article on How to Calculate Voltage Dividers for Power Supply Devices. A copy will be sent free on request.

AEROVOX

"Built Better"

78 Washington St., Brooklyn, N. Y.

1929

ALUMINUM CONDENSERS

SEVERAL years ago one of the leading radio producers asked Aluminum Company of America for a special close tolerance aluminum condenser blade stock. Specifications required that variations in thickness within a single sheet should be less than .0005" and the gauge tolerance from sheet to sheet ±.001". By a special process aluminum sheet was produced that was satisfactory both in gauge and flatness. Other radio manufacturers were quick to adopt this special "radio flat sheet". This material has been produced in quantity for two years and has been of uniform high quality. Aluminum is the logical material for the "heavy" condenser blades now required in sets that are housed in the same cabinets with powerful loud speakers. Aluminum blades do not vibrate and produce microphonics. A variety of efficient assembling methods are applicable to aluminum, such as die-casting, staking and swedging. Maintenance on tools used for punching aluminum blades is negligible. Aluminum condenser blades will be found in the great majority of the new sets in 1929.

ALUMINUM SHIELDING

SHIELDING will be universal in 1929 sets because it permits engineers to use the highest gain per stage of amplification in their new designs. Aluminum shielding was successfully used on 22 leading sets last year. Five other prominent manufacturers are either adopting aluminum shielding or returning to it. The reason is evident. Aluminum is highly efficient electrically, especially at radio frequencies. It works easily and well in the shop. It has its appeal to both purchaser and producer, because it is attractive in appearance, light in weight and non-corrosive. It adds the mark of quality to a set. Aluminum just naturally possesses the right qualities for radio shielding. Aluminum shields will be found to be economical in first cost, in production and in finishing.

* * *

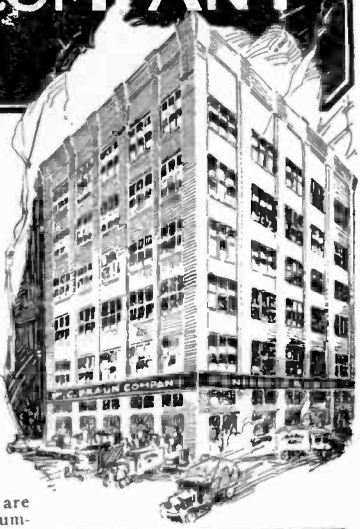
ALUMINUM COMPANY OF AMERICA produces aluminum and its alloys in every commercial form. Also magnesium products. Aluminum foil is the best material for fixed condensers. Radio manufacturers use aluminum sheet, wire, rod, tubing, stampings, die-castings, sand-castings, strong alloys, extruded shapes, screw machine products, aluminum wood grain panels and other aluminum parts to advantage. Inquiries are solicited.

ALUMINUM COMPANY OF AMERICA
ALUMINUM IN EVERY COMMERCIAL FORM
2470 Oliver Building, Pittsburgh, Pa.
Offices in 19 Principal American Cities

ALUMINUM

The mark of Quality in Radio

W.C. BRAUN COMPANY
WHOLESALE RADIO HEADQUARTERS



Abreast of the New Developments in Radio

No industry in the world's history has attracted so many inventors and experimenters as the radio industry. Something new is always on tap. Contrast the old wireless days with the modern electrically operated talking radio. Think of what is still to come when perfected television, telephony, short wave control, etc., are fully realized.

In keeping with the policies of *Wholesale Radio Headquarters* (W. C. Braun Company), our service lies in testing out and determining which of these newest marvels are practical, salable and usable for the greatest number. Our task is to study the multitude of new merchandise, select those items that are thoroughly proved and reliable, and make it easy for the public to secure these while they are still new.

A huge and varied line of standard radio merchandise is carried in stock for quick shipment to all parts of the country. This service assures the dealer and set builder of *everything he needs,* all obtainable from one house, without shopping around at dozens of different sources. It saves considerable time, trouble and money. For example, when you want a complete radio set or parts for a circuit, you also will want a cabinet, loud speaker, tubes and other supplies and accessories. You know that at Braun's you can get everything complete in one order, and thus save days and weeks of valuable time, besides a considerable saving in money.

New Lines for Spring and Summer

Here, all under one roof, is carried the world's largest stocks of radio sets, kits, parts, furniture, speakers and accessories for the radio season, portable radios and phonographs for summer trade and a complete line of auto tires, tubes and supplies, electrical and wiring material, camping and outing equipment, tents, golf goods, sporting goods; in fact, a complete merchandise line to keep business humming every day, every week and every month in the year.

NEW LINES
SPRING and SUMMER

RADIO SETS, KITS, PARTS SHORT WAVE, TELEVISION, SPEAKERS, SUPPLIES, PORTABLE RADIOS and PHONOGRAPHS AUTO TIRES and ACCESSORIES

ELECTRICAL GOODS
Wiring Fixtures, Etc.

SPORTING GOODS
Outing Clothing, Baseball, Golf Goods, Etc.

HOUSEHOLD SPECIALTIES
Vacuum Cleaners, Phonographs, Electrical Toys

Do You Get Our Catalog?

If you don't receive our catalog, by all means send us a request on your letterhead to insure getting each new edition as promptly as it comes out. Braun's Big Buyers' Guide is crammed full of bargains and money-making opportunities that you cannot afford to pass up.

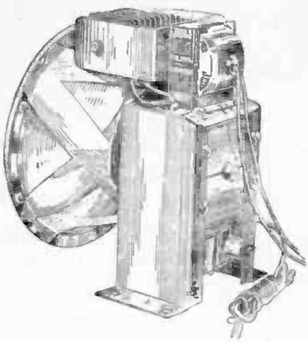
W. C. BRAUN COMPANY

Pioneers in Radio

600 W. Randolph St., Chicago, Illinois

TEMPLE

The New
TEMPLE DYNAMIC
Speakers



ADD to the approved and accepted principle of sound reproduction the compelling significance of the Temple name and the result is a product which again sets a new standard in speaker excellence.

Temple Dynamics are made only as Temple can make them—that means better.

"They Speak for Themselves"

Available to manufacturers in three chassis models:

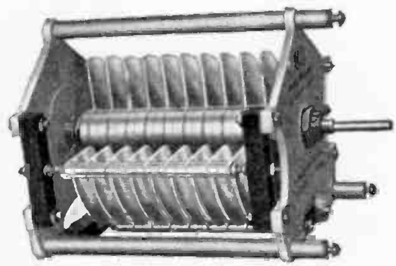
Model 10, 110 volt, A.C., 60 cycle
Model 12, 110 volt, A.C., 25 cycle
Model 14, 110 volt, D.C.

Write for full particulars

TEMPLE CORPORATION
1925 S. Western Ave., Chicago, U. S. A.

LEADERS IN SPEAKER DESIGN

When Designing for Higher Efficiency Use REL Condensers and Inductors



Cat. No. 127 Type "LL" inductances used in conjunction with Cat. No. 149 high voltage variable condensers make highly efficient tank circuits in installations of any power up to 2KW. Flatwise wound—Low distributed capacity—Moulded Glass separators—Low Losses—95% Air Dielectric—Mechanically rugged—Unaffected by climatic conditions—These are merits which warrant the use of this inductance in first class stations—Any number may be connected in series for any frequency—Adaptable to Master Oscillator Power Amplifier—Coupled Hartley-Meissner—Culpitts—Tuned Grid Tuned Plate, and many other popular circuits. Especially suited for broadcasting installations—Conveniently mounted—occupies a minimum of space. When redesigning broadcast stations, engineers turn to REL products.

Cat. No. 149 variable condensers have many uses in high powered stations—Type R rating at 25 mmfd, 10,000 volts is adaptable for neutralizing Power amplifiers and for vernier adjustment when paralleling main tank condenser to keep frequency to zero beat with crystal monitor—Type P rating at 180 mmfd 5000 volts adaptable to main tuning and antenna series control in medium powered outfits—Types K, L, M rating 200 to 650 mmfd, 3000 volts, adaptable to main tuning control in low powered transmitters—Features are: Heavy Brass Plates—Substantial Cast Aluminum End Plates—Steel Shaft projecting through both ends—Cone Bearings with locking device—Isolantite Stator supports—Super-Construction throughout.

For information on the REL Inductances as given in Bulletin 27, data on the variable condensers as furnished on Bulletin 39, these two pamphlets will be sent upon request.

REL MANUFACTURES A COMPLETE LINE OF APPARATUS FOR SHORT WAVE TRANSMISSION AND RECEPTION

RADIO ENGINEERING LABORATORIES

100 Wilbur Ave. Long Island City, N.Y., U.S.A.

Tone Control

Of course you have developed your amplifier, loud-speaker and electric phonograph pickup to the point where magnificent tone quality is available. However, unless you can *control* that tone quality *without distortion,* you have not completed your engineering job.

The TABLE TYPE CLAROSTAT or, if preferred, the built-in Volume Control Clarostat, is the solution of the tone control problem. It is compact, simple, inexpensive, practical. Just the thing for the electric phonograph pickup. Ideal as a loud-speaker control, particularly in centralized radio installations. The extension cords permit of ready use, without tools. A favorite in controlling the volume of A-C tube harnesses.

But after all, the TABLE TYPE CLAROSTAT is only typical of the Clarostat line, which includes a variable resistor of the proper size and style and range for every radio purpose. From the Grid Leak Clarostat and built-in Volume Control, to the Speed Control Clarostat for television scanning disk regulation, you will find just the right device for your present and future resistance problems.

Write for data regarding the TABLE TYPE and other types of Clarostat. And do not hesitate to place your resistance problems before us. If you are not receiving our technical bulletin issued from time to time, ask for it.

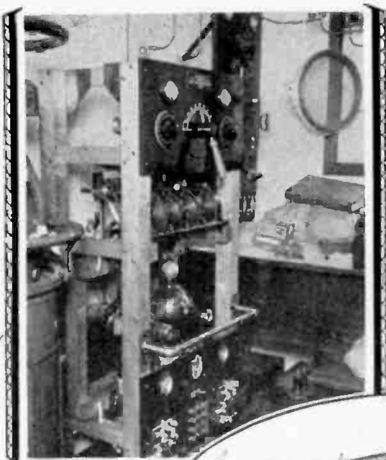
Clarostat Manufacturing Company, Inc.

MEMBER RMA

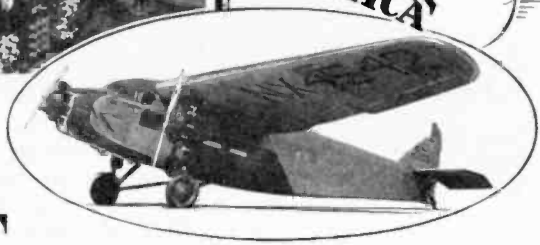
Specialists in Variable Resistors

289 N. Sixth St. :-: Brooklyn, N. Y.

CLAROSTAT
REG. U. S. PAT. OFF.



BYRD'S RADIO *is insulated with* FORMICA



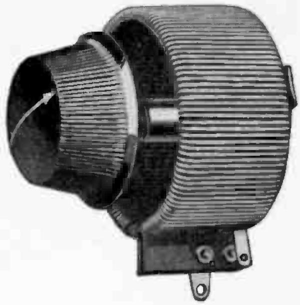
Formica was used by the engineers who designed the sending and receiving apparatus in use by the expedition, for panels, tubing, and other insulating parts.

For fifteen years American radio men have known it as excellent insulation for high or low frequency uses. It is high in quality and uniform—Phenol Fibre at its best.

Every year millions of automotive ignition systems, therapeutic apparatus, circuit breakers and electrical devices of all kinds are insulated with Formica. You can depend upon it.

THE FORMICA INSULATION COMPANY
4646 SPRING GROVE AVENUE
CINCINNATI, OHIO

FORMICA
Made from Anhydrous Bakelite Resins
SHEETS TUBES RODS



Giant Power Rheostat

SMALL IN DIAMETER, but large in capacity, this rheostat will safely carry any power load of 70 watts. Constructed of heat proof materials throughout. There is no fibre to warp or burn out. Wire is wound on a steel core insulated with asbestos. Extra wide core assures large area for quick heat dissipation.

This unit is ideal for primary control of "AC" receivers or "A" Power Units. It will keep the line at a constant workable average, keeping the secondary output well within rated limits. These units connected in series across the output of a Rectifier and Filter system for "B" Power will provide all necessary voltage taps.

These units can be used in any power circuit position without any danger of burning out—the capacity is only limited by the capacity of the wire.

Manufactured with two or three terminals. Diameter 2", depth $1\frac{1}{4}$". Write for new booklet on "Volume Controls and Voltage Controls—their use."

Centralab

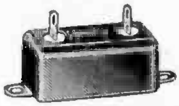
CENTRAL RADIO CRL LABORATORIES

16 Keefe Ave. Milwaukee, Wis.

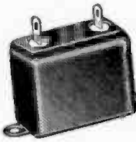
A CENTRALAB CONTROL IMPROVES THE SET

Condenser Specialists

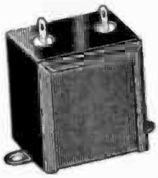
Offer an Unusual Service to Set Manufacturers

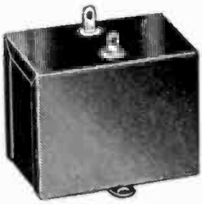


Millions of Fast by-pass and filter condensers are in daily use in radio sets made by the leading set manufacturers. They are renowned for their high insulation resistance and excellent and dependable electrical characteristics.

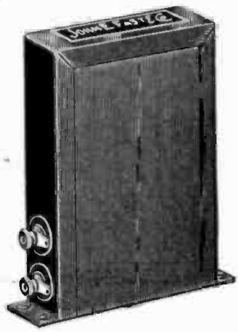


Manufacturers looking for a dependable source of supply, keyed to meet large production problems, on short notice, will find here one of the largest organizations of its kind in the world.





We make one thing and one thing only—wax impregnated paper condensers in die-press steel jackets, in medium and large capacities to fit every known need in radio sets, power units, etc. We make no set hardware, no eliminators, no transformers, no parts, no sets. Our entire concentrated effort is on one product alone—condensers. Such specialization assures highest quality, economical production and real service.



Send us your specifications.

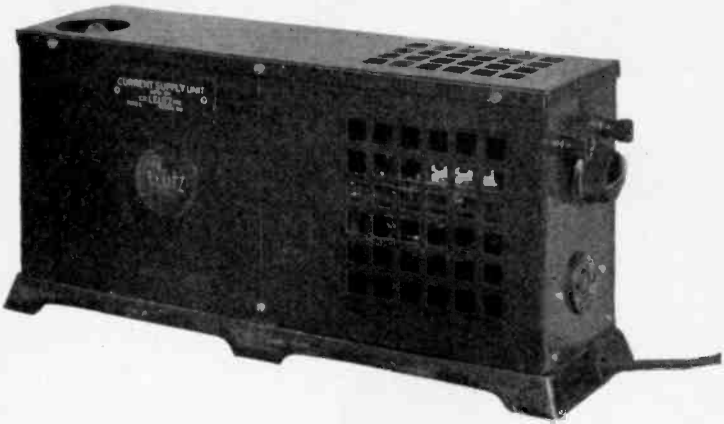
JOHN E. FAST & Co. MEMBER R.M.A.

Established 1919

3982 Barry Avenue, Chicago, U.S.A.

LEUTZ "A" Current Supply

For Laboratory and Experimental Work



Maximum Capacity 3 amperes
at 6 volts. Free from "Hum."

SPECIFICATIONS

Line Supply. 110 volts, 60 cycles A.C. standard. Also made for 220 volts 50/60 cycles.

Output. Full three amperes at 6 volts and without any hum when used on radio receivers.

Construction. A Full Wave Dry Rectifier is used, the output being thoroughly filtered by a heavy choke and very large condenser.

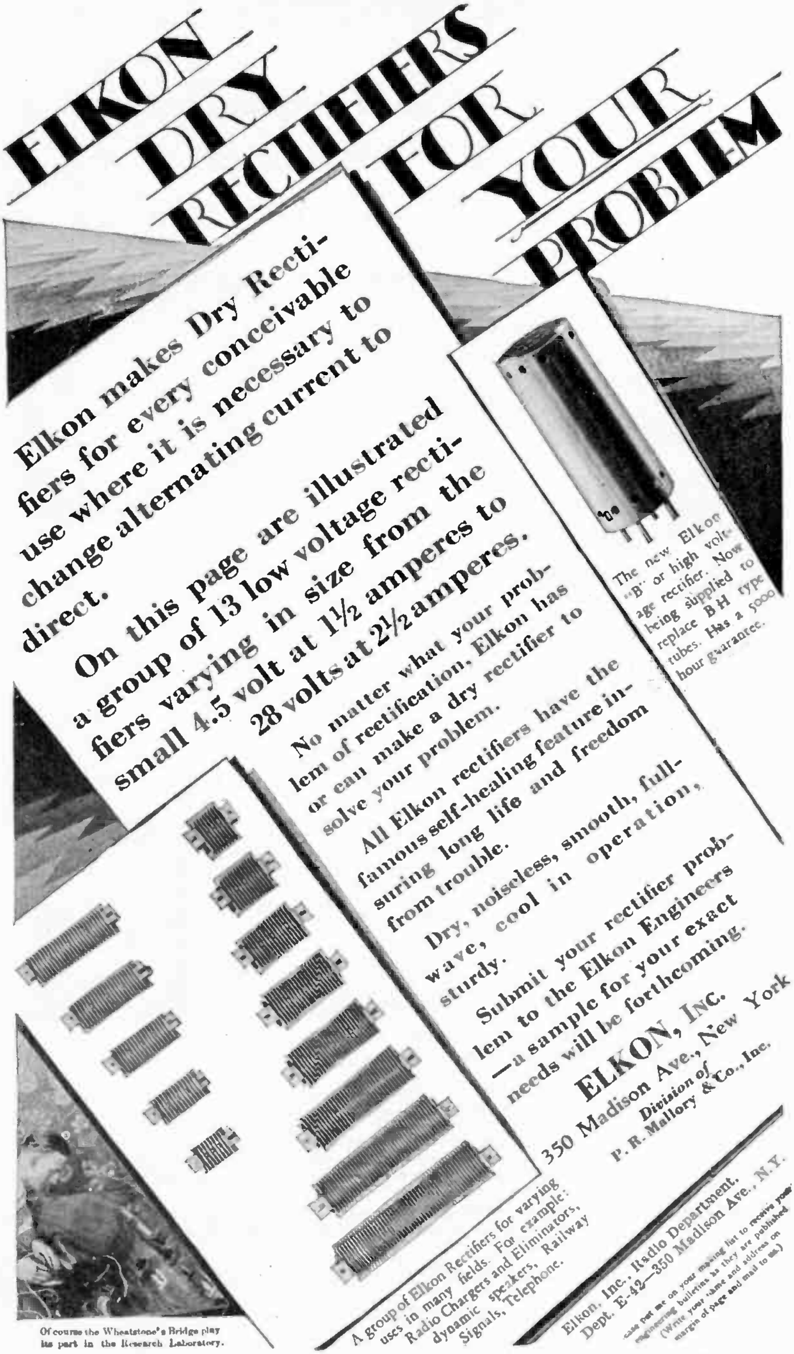
Regulation. An adjustment is provided to regulate the filament voltage where the output load is less than 3 amperes.

Ideal for Radio Laboratories
Literature and Prices on Request

C. R. LEUTZ, *Inc.*

195 Park Place, Long Island City, New York

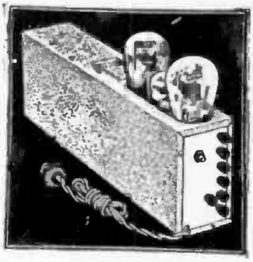
Cables "*Experinfo*" N. Y.


ELKON DRY RECTIFIERS FOR YOUR PROBLEM
Elkon makes Dry Rectifiers for every conceivable use where it is necessary to change alternating current to direct.
On this page are illustrated a group of 13 low voltage rectifiers varying in size from the small 4.5 volt at 1½ amperes to 28 volts at 2½ amperes.
No matter what your problem of rectification, Elkon has or can make a dry rectifier to solve your problem.
All Elkon rectifiers have the famous self-healing feature insuring long life and freedom from trouble.
Dry, noiseless, smooth, full-wave, cool in operation, sturdy.
Submit your rectifier problem to the Elkon Engineers—a sample for your exact needs will be forthcoming.
ELKON, INC.
350 Madison Ave., New York
Division of
P. R. Mallory & Co., Inc.
The new Elkon "B" or high volt-age rectifier. Now being supplied to replace BH type tubes. Has a 5000 hour guarantee.
A group of Elkon Rectifiers for varying uses in many fields. For example: Radio Chargers and Eliminators, dynamic speakers, Railway Signals, Telephone.
Of course the Wheatstone's Bridge play its part in the Research Laboratory.
Elkon, Inc., Radio Department, Dept. E-42—350 Madison Ave., N.Y.
(Write your name and address on margin of page and mail to us.)

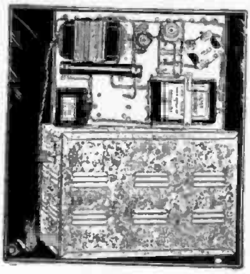
SM

S-M Tone Quality for One Speaker or a Thousand

678PD Phonograph or Radio Amplifier



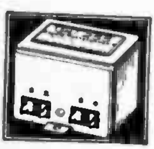
A compact two stage amplifier, of a type similar to that made by S-M for several theatrical phonograph manufacturers. From radio or record input, it will develop 4500 milliwatts undistorted power to cover up to 2,000 seat theaters when feeding two dynamic speaker units in 40 inch baffles (to one dynamic unit it supplies field current if desired). Ideal also for home use. Tubes used: one each '26, '81, and '50. Price, WIRED, ready to operate, $73.00; or KIT, complete, $65.00.

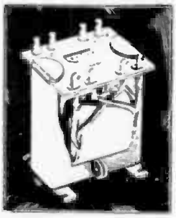


685 Voice, Record or Radio Power Amplifier

The 685, for portable use, as utilized by the U. S. Shipping Board exhibits at many state and county fairs, gives coverage of 2,000 seat or larger auditoriums, or outdoor crowds of up to 15,000, with optional voice, radio, or record input. Price, 685 Unipac, WIRED, ready to operate, $160.00, or 685 KIT, complete, $125.00.

Announcing New PUSH-PULL APPARATUS





And now, S-M is glad to announce new super-quality push-pull audio transformers built on the Clough system, all offering curves flat from below 50 cycles to well above 5,000 cycles—transformers that give to "push-pull" a new and really startling significance. And their prices like their quality are unbeatable!

The new 257 is a push-pull input type, to operate from one amplifier tube into two 171A, 210, or 250 tubes, and lists at the low price of only $7.00. Type 227 is a push-pull inter-stage transformer, to feed from two 112A, 226, or 227 tubes into two 112A, 226, 227 or 171A, 210 or 250 tubes, and lists at $8.00.

Type 258 tapped output impedance is intended to feed from two 171A tubes into any standard speakers. Price $5.00. Type 248 Universal output choke is designed to feed out of two 210 or 250 tubes into one to six or more standard speakers, and is provided with several impedance-matching taps. It will handle over 20 watts without core saturation. Price, 248 open mounted $7.00; or 228 (in same case as 227) $8.00.

Remember—S-M guarantees these push-pull transformers to have a finer frequency characteristic than any and all competitive types—bar none.

Full information is contained in S-M Data Sheets—No. 2 on 685 Amplifier, and No. 9 on 678 PD Amplifier. Ask also for our new General Catalog, containing description of higher-power amplifiers, and Radiobuilder No. 9, describing new push-pull apparatus.

SILVER-MARSHALL, Inc., 862 W. Jackson Blvd.
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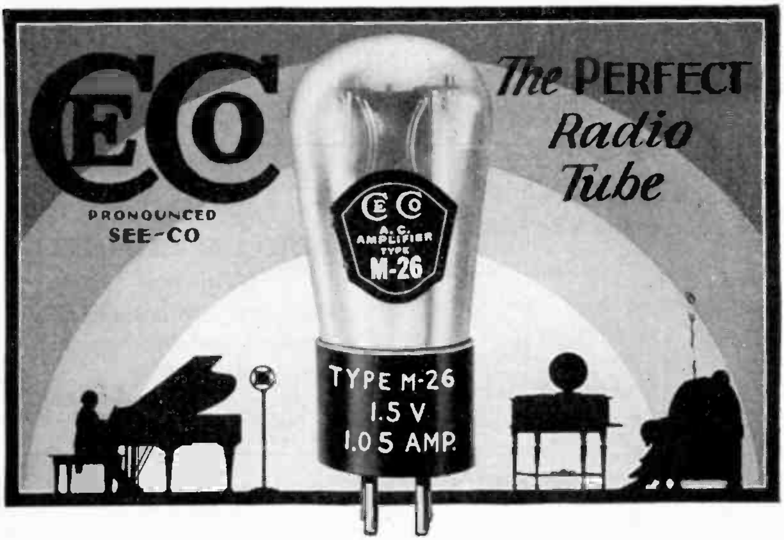

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Patient laboratory experimentation over a period of years has combined with this tone beauty a durability which makes them the most economical tube to use. They cost no more but last longer.

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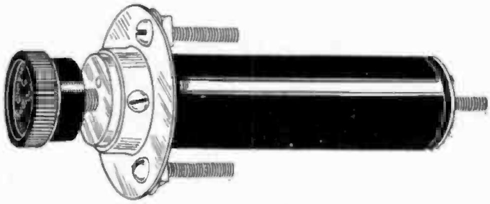

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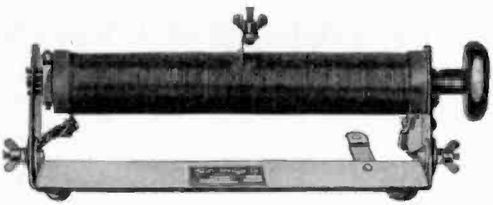

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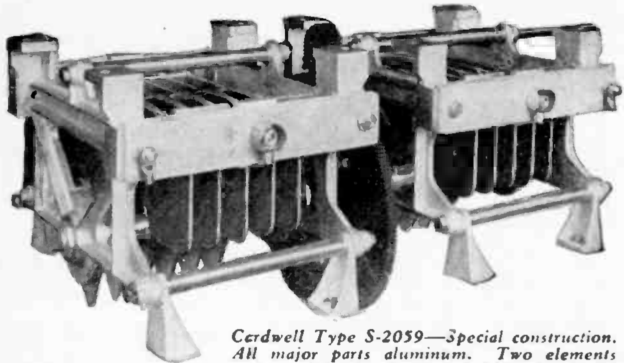

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To get down to "brass tacks," though, the point we wish to make is that they didn't come to CARDWELL for jewelry, nor for tinware.

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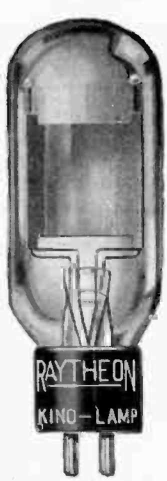
Television sending tube in hard vacuum or gas filled types



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Price $7.50

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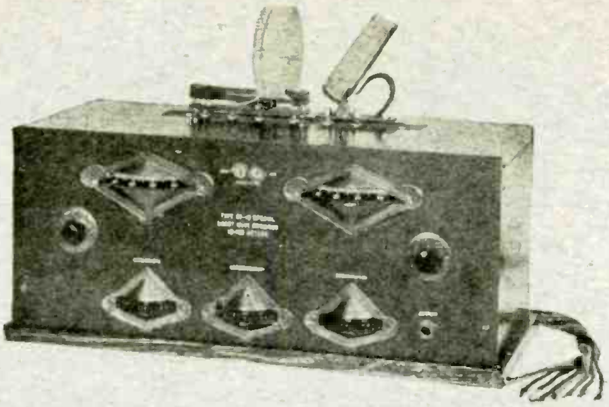

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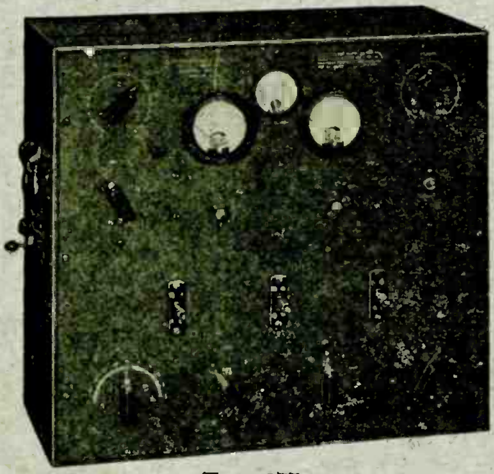
Vacuum-Tube Oscillator



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Vacuum-Tube Oscillator
Price—$350.00

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